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Lasershot^{sm} Marking System: High-Volume Labeling for Safety-Critical Parts

C. B. Dane, L. Hackel, J. Honig, J. Halpin, H-L. Chen, F. Mendieta, F. Harris, L. Lane, J. Daly, J. Harrison

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Lawrence
Livermore
National
Laboratory

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2001 R&D 100 Entry

Lasershot^{sm} Marking System: High-Volume Labeling for Safety-Critical Parts

Submitted by

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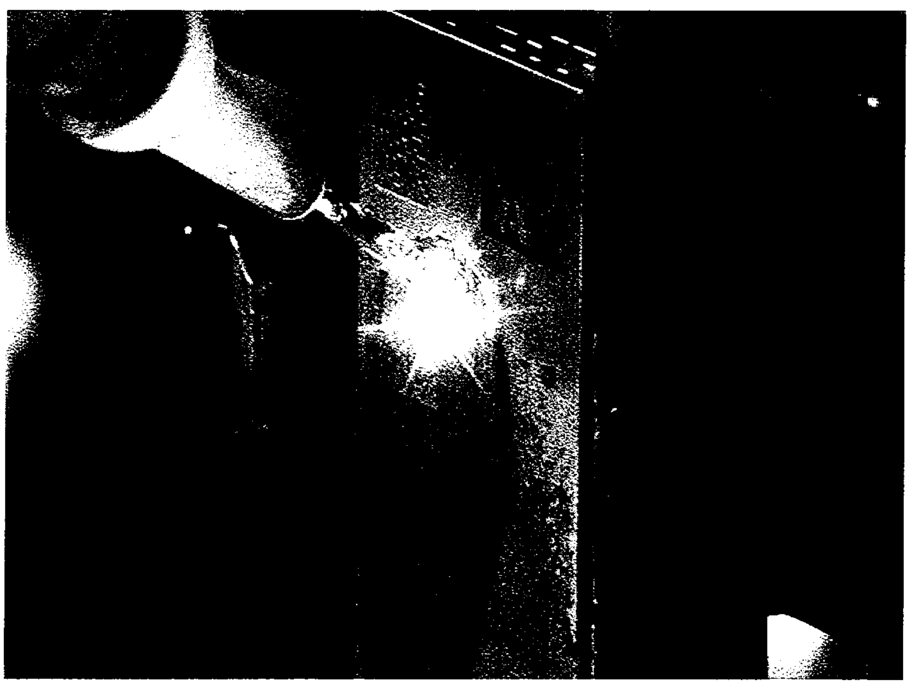
and

Fritz Harris, Laurie Lane, James Daly, and James Harrison
Metal Improvement Company, Inc.



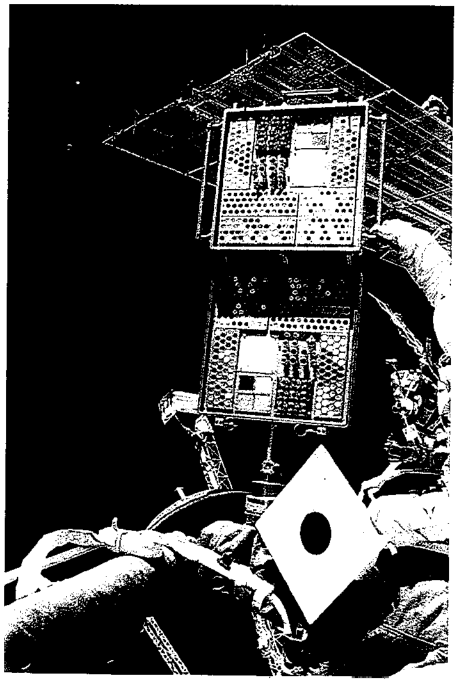
The Lasershot^{sm} Marking System imprints an identification mark that is

- permanent
- machine readable
- high resolution

without weakening the surface of the marked part. Now, for the first time ever, manufacturers can mark parts used in safety-critical applications without the danger of fatigue and stress-crack corrosion induced by other marking methods.

2001 R&D 100 Awards Entry Form

Lasershot^{sm} Marking System: High-Volume Labeling for Safety-Critical Parts



Lasershot^{sm} marked parts will be part of the Materials International Space Station Experiment (MISSE), the first science experiment on the International Space Station. The MISSE is scheduled to be launched on the Space Shuttle in June 2001.

Lawrence Livermore National Laboratory and Metal Improvement Company, Inc.

The Lasershot^{sm} Marking System uses laser pulses to safely and permanently impress identification markings on metal components.* This process does not remove material or change surface chemistry and actually increases the marked area's resistance to fatigue and corrosion failure. Lasershot^{sm} marking is ideally suited for marking parts used in situations where safety is critical—from hip-joint replacements to commercial airliner components. The minimum size of the mark is limited only by the resolution of the reading system, allowing manufacturers to mark parts which, up to now, have been too small to label with mechanical peening techniques. The high resolution of the Lasershot^{sm} marks makes them difficult to reproduce, providing a solution to the on-going problem of inferior, counterfeited parts. The high marking rate of up to six marks per second makes this system practical and cost-effective for marking high-volume components.

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*Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract no. W-7405-ENG-48.

A Lasershot^{sm} marked sample of aerospace-grade titanium alloy. The characters **"2001 R&D 100 Awards"** are encoded in this 18x18 Data Matrix.

2001 R&D 100 Awards Entry Form

1. **Submitting organization:**	Lawrence Livermore National Laboratory
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AFFIRMATION: I affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product.

Submitter's signature:________________________________

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3. **Product name:** Lasershot^{sm} Marking System

4. **Briefly describe what the entry is:**
The Lasershot^{sm} Marking System uses a pulsed solid-state laser system to apply recessed identification markings to metal components. The resulting permanent, high-resolution marks are machine readable, resistant to fatigue and stress-crack corrosion, and resist counterfeiting.

5. **When was the product first marketed or available for order?**
The Lasershot^{sm} Marking System was first available in September 2000.

6. **Inventor or principal developer:**
List additional developers on separate sheets in an appendix and check here [X].

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7. **Product price:** If the price is proprietary, list it and check here [X].
The overall system cost for the Lasershot^{sm} single-shot pattern marking system (which also provides high capacity laser peening) is $2M and for the multiple-shot matrix marking system is $200k. The cost to mark each part with a laser-peened identification is approximately $6. Based on the highly competitive nature of the parts marking industry, this pricing is proprietary to Metal Improvement Company, Inc.

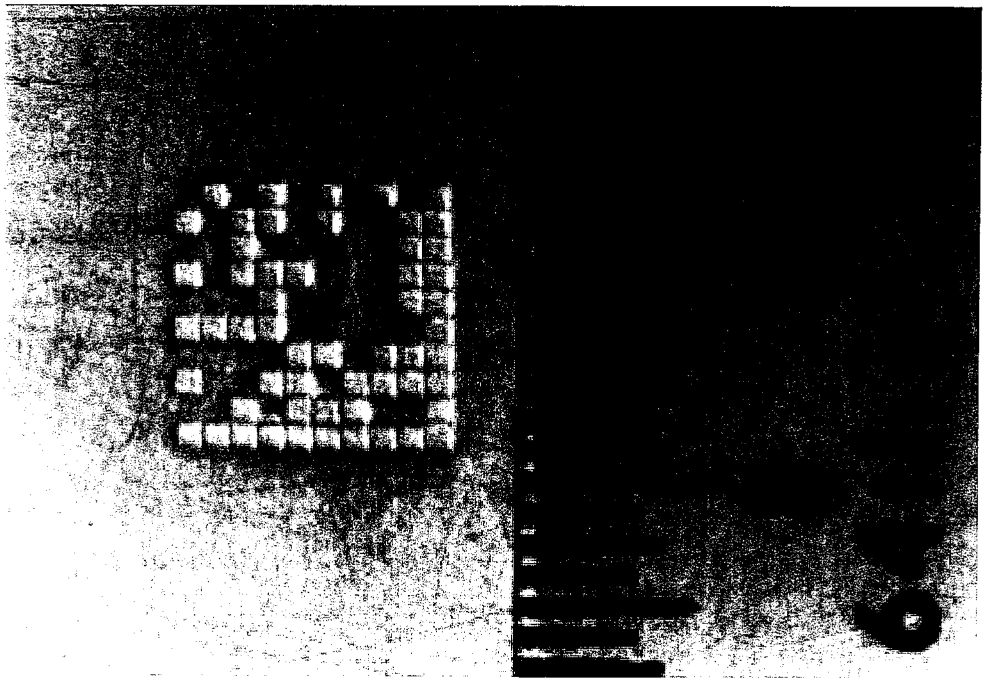
8. **Do you hold any patents or patents pending on this product?** Yes [X] No [ ].
A patent application was submitted for the peen marking process in July, 2000 and for the optical imaging system on which the marking system relies in August, 1998. The claims of the latter application have been fully allowed and the patent will be issued shortly. U.S. Patents 5,239,408 (August 24, 1993) and 5,689,363 (November 18, 1997) describe the laser technology used in the Lasershot^{sm} Marking System.

9. Product description.

What does it do? The Lasershot^{sm} Marking System permanently marks individual parts, providing positive part identification, after-market traceability, protection against counterfeiting, and fewer data transcription errors. Other permanent-marking processes depend on etching, rapid heating, or scribing, all of which weaken the marked area, causing it to be a potential source for crack initiation. Because the Lasershot^{sm} marking process uses an intense pressure pulse that is generated by an incident laser beam, no material is removed and the area marked gains residual compressive stress. This compressive stress prevents cracks from forming or growing, and the resulting mark is actually more resistant to stress or fatigue failure than the surrounding surface of the part. Lasershot^{sm} marking is the only method available for permanently labeling safety-critical parts without weakening the part.

The Lasershot^{sm} Marking System can print any pattern, including one-dimensional bar codes, two-dimensional symbols, and human-readable characters. The system is ideally suited for imprinting the "Data Matrix," a high-data-density, two-dimensional, machine-readable symbol first developed by RVSI Acuity CiMatrix for the National Aeronautics and Space Administration (NASA) to identify and track the millions of parts used in the space program. Although the Data Matrix is currently in use to track the thousands of heat-resistant tiles on the Space Shuttle, safety-critical metal parts are not marked because of the risk of marking-induced failure.

How does it work? In the laser peening process a thin layer of absorptive material is placed over the area to be peened and a layer of water approximately 1mm thick is flowed over the absorption layer. A high-intensity laser with a fluence of approximately 100J/cm^2 and a pulse duration of 15ns illuminates and ablates material from the absorption layer, creating an intense pressure pulse that is initially confined by the water. The absorption layer protects the part surface from material removal or melting. The pressure pulse creates a shock wave that strains the metal surface in a two-dimensional pattern directly correlated to the laser's intensity profile at the surface. By creating a desired pattern upstream in the light field and imaging this pattern onto the metal surface, the entire desired pattern is pressure printed with a single laser pulse. By employing spatial light modulation of the near field beam and then imaging this pattern onto the metal, a completely new Data Matrix, for example, can be created with each laser pulse. This single-pulse technique—Lasershot^{sm} *pattern* marking—prints a complete pattern with each laser pulse and is thus particularly well suited for high-volume marking applications. In an alternate approach—Lasershot^{sm} *matrix* marking—the two-dimensional Data Matrix is built up of multiple laser pulses. This alternate technique addresses lower-volume markets and has the benefit of requiring a less expensive marking system.



A 10x10 Data Matrix imprinted into an aviation-grade aluminum alloy (2024T3 aluminum) using the Lasershot[sm] pattern marking technique with only a *single* laser pulse. The Data Matrix is machine readable and can contain up to 100 times more information than a linear bar code in the same or less space. The mark shown above is only 1/8 inch on a side and is easily read with the RVSI CiMatrix handheld reader.

10a. Product competitor methods.

The primary competitive technologies to the Lasershot^{sm} Marking System are laser etching, pin stamping, and ink jet marking. These can be summarized as follows:

Laser etching – Laser etching markers work by focusing energy directly on the surface to be marked. The heat generated by the beam actually alters the surface of the part or vaporizes surface material. In the case of steel, when the temperature is raised in a localized area, carbon will precipitate out along grain boundary areas, turning the surface black. In other metals, the surface is etched when material is removed by high temperature vaporization. Although this technique has good permanence and generates a clear mark with good contrast, it modifies the metal alloying and etches the surface in a way that degrades the part's strength and can lead to fatigue or stress-corrosion crack failure. It is important to contrast laser etching with our Lasershot^{sm} marking technique which involves no material removal or changes in the surface chemistry.

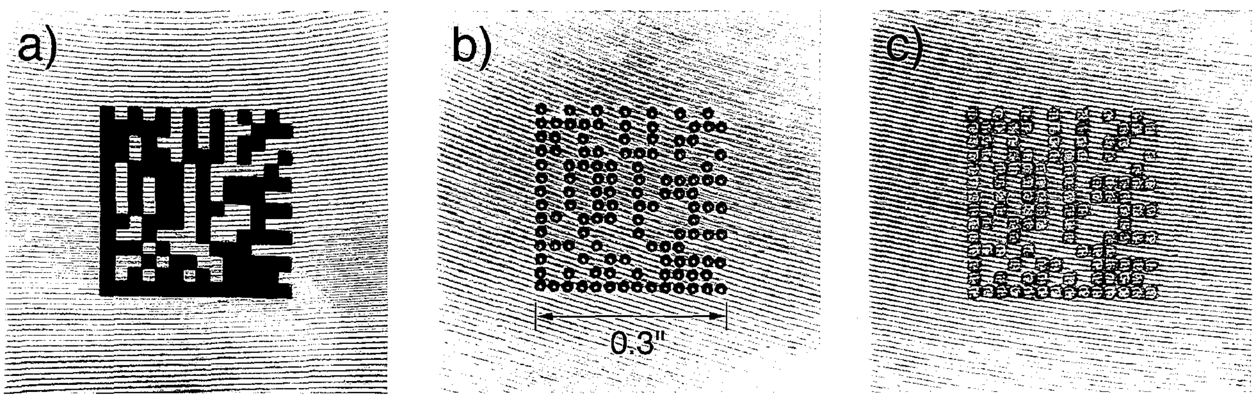
Pin stamping – In pin stamping, a marker stylus impacts the surface of the material being marked. Due to the conical shape of the stylus, the size of a marked cell is controlled by the penetration depth. Pin stamping may leave a residual compressive stress in the part to provide some protection against fatigue and mechanical stress. However, the benefits of this compressive stress are most likely outweighed by the detrimental effects of the surface roughening and the stress concentration at the bottom of the sharp indentations. Also the risk of distortion or damage to small parts or parts with thin cross sections is unacceptably high. Wear of the mechanical stylus against hardened parts also poses a significant disadvantage.

Ink jet – Ink jet printers propel ink droplets from the printing head to the part surface. The permanence of the mark depends on the chemical interaction between the ink and the part as well as on the environment to which the part is exposed. The durability of the mark is not acceptable for typical environments of safety-critical metal parts. The minimum size of the mark is limited by the resolution of the print head and the required stand-off from the part, making the marking of very small parts difficult or impossible.

Other techniques – Other less common permanent marking techniques include sandblasting, machining or engraving, chemical etching, and welding. Each of these results in clearly unacceptable degradation in a metal part's strength and fatigue lifetime. Techniques have been developed to safely cast symbols onto part surfaces during manufacturing. However, the mold marking method is generally limited to larger parts and does not address the need to mark already manufactured parts or those produced by forging, machining, and other methods beside casting.

10b. Competitor comparison matrix.

	Lasershot^{sm} marking	Laser etching	Pin stamping	Ink jet marking
Readability of mark	Good	Good	Good	Good
Mark recessed from surface for wear-resistance	Yes	No	Yes	No
System performs non-contact marking	Yes	Yes	No	Yes
Permanence of mark	Good	Good	Good	Poor
System able to mark small parts/thin sections	Yes	Yes	No	No
Fatigue resistance of marked area	Excellent	Poor	Not known	Same as before marking
Resistance of mark to counterfeiting	Very high	Moderate	Low	Low



The photographs above illustrate three marking methods using the same 14x14 Data Matrix array in 4340 steel: a) laser etching, b) pin stamping, and c) Lasershot^{sm} marking (using the multiple laser-pulse matrix marking technique). Lasershot^{sm} marking provides a clear, easily readable identification mark while preserving or even enhancing the resistance to crack initiation in the treated area. For the purposes of this test, the surfaces have been intentionally left with a machined surface roughness of 150µm RMS before marking, clearly visible in the photographs.

10c. Improvement upon competitive products or technologies.

The key feature of Lasershot^{sm} marking technology is the use of an intense pressure pulse, which exceeds the yield strength of the metal part and causes a mechanical indentation in the part's surface. Unlike laser etching, no material is removed and there is no chemical modification of the marked surface. In fact, a strong compressive stress is left in the surface of the part, making it more resistant to fatigue or stress-corrosion cracking failure. Unlike the pin-stamped mark made using a pointed stylus, the laser-peened mark does not exhibit material flow (cratering) around the edges, minimizing detrimental cold work effects. Also, unlike mechanical peening techniques, it has been shown that the compressed protective layer from laser peening extends as deep as 1mm into the metal[1] and can extend the useful life of stress critical parts by up to ten times[2]. We believe that this makes Lasershot^{sm} marking the first and only solution available for the permanent, direct surface marking of safety-critical metal components.

A breakthrough in laser technology employing a Nd:glass laser and a wavefront correction technology called phase conjugation now enables the building of a laser system that can operate at up to 6 pulses per second with output energy of >25J. This represents a fundamental capability of peen marking 6 complete data matrices per second using the single-shot pattern marking technique. Nonlinear phase conjugation provides a high quality beam with very high long-term pointing stability. Even for the smaller laser-pulse energies required for the matrix marking approach, phase conjugation provides beam quality and pointing stability for the high repetition frequencies needed for optimal part throughput. The result is part treatment rates that are comparable to or exceed conventional marking methods.

Finally, beam delivery to the part is critical to accurately replicate the desired two-dimensional marking pattern. The output from the laser is precisely relay imaged onto the surface of the part. A specially designed telescopic delivery system has been designed which provides this imaging without requiring that the beam pass through focus near the part as would usually be the case. Creating the optical pattern with fine detail in the near-field beam means that the resulting mark on the part will also have uniquely embossed fine detail and will therefore be nearly counterfeit-proof, much like watermarks on modern currency.

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[1] C. B. Dane, L. A. Hackel, J. M. Halpin, J. Daly, J. Harrisson, and F. Harris, "High-throughput laser peening of metals using a high-average-power Nd:glass laser system," *SPIE Proceedings 3887-21*, contributed paper HPL03, November, 1999.

[2] R. B. Thakkar, R. P. Shah, and V. Vanark, "Effects of hole processes and surface conditioning on fatigued behavior of aluminum-6061-T6," *SAE World*, March, 2000.

11a. Principal applications of this product.

The primary use of this marking system will be with safety-critical, highly stressed or fatigued metal parts from across the aerospace, automotive, and biomedical engineering industries. As the design of parts becomes increasingly sophisticated, there is a growing effort to make critical parts thinner and lighter while continuing to place them under the same mechanical load. This trend, combined with the requirement to accurately and permanently mark parts for identification and tracking, creates the need for a surface marking solution that does not make the part vulnerable to fatigue or stress-crack corrosion failure. An excellent illustration is provided by a recent study of ten patients who underwent total hip replacement only to experience fatigue fracture of the implant as soon as nineteen months later.[3] Scanning electron micrographs of five of the ten fractured prostheses demonstrated a fatigue fracture that began through characters that had been etched on the patient's joint implant with a laser. In these cases, the disturbance of the surface caused by the marking method directly lead to the failure of the medical implants and the failures would have been prevented by the Lasershot^{sm} marking method.

An important application of our process will be the marking of safety critical parts used in the Space Shuttle and the International Space Station with the Data Matrix symbol devised by RVSI Acuity CiMatrix. NASA recently added Lasershot^{sm} marking to its Data Matrix Direct Part Marking Standard (NASA-STD-026) and Handbook (NASA-HDBK-027). NASA and the Department of Defense are also conducting ground, flight, and in-orbit marking tests to certify laser peen marking's use in both current and future programs. NASA Langley's Materials International Space Station Experiment (MISSE) will investigate the effects of radiation and other environments on approximately 1,500 samples housed in passive experimental containers that will be attached to the exterior of the Space Station for up to 3 years. Among these samples will be those imprinted with the Lasershot^{sm} marking process. The parts will be carried on Space Shuttle Mission STS-105 in late June 2001.

The Air Transportation Association (ATA), the Electronics Industry Association (EIA), the Automotive Industry Action Group (AIAG), and the Semiconductor Equipment Manufacturers' Institute (SEMI) have also chosen the Data Matrix as the preferred parts marking standard. This widespread acceptance of the Data Matrix extends the potential applications for the Lasershot^{sm} process. The peen marking technique is ideal for permanent identification marking of safety-critical aircraft components such as fan

[3]S. T. Woolson, J. P. Milbauer, J. D. Bobyn, S. Yue, and W. J. Maloney, "Fatigue Fracture of a Forged Cobalt-Chromium-Molybdenum Femoral Component Inserted with Cement," *The Journal of Bone and Joint Surgery* **79**, 1842-48 (1997).

blades, discs, rotors and integrated rotor assemblies as well as for the safety-critical components in the automobiles that we drive.

11b. Other applications for which our product can now be used.

We expect that the market for this technique can expand well beyond its principal applications to metal parts used in environments other than the safety-critical, high-stress, corrosive environments discussed above. The inherent desirable characteristics of the surface-recessed Lasershot^{sm} mark for metals, including high part-throughput, good readability, and excellent durability should make it a valuable labeling technique for a wide variety of parts in industrial manufacturing. A 747 commercial airliner has over 4 million parts, including landing gear and other structural components. Although many of these components are not safety-critical, current manufacturing standards require that each of these parts be identified and traced from cradle-to-grave. Peen marking is also a solution for challenging labeling applications of items such as gears, bearings, and springs.

12. Summary

We have developed a unique labeling process call Lasershot^{sm} Marking that for the first time enables the permanent surface marking of safety-critical metal parts. The process supports the new industrial standard Data Matrix encoding system and, unlike competitive technologies, peen marking does not use etching, rapid heating, or scribing which can leave the surface susceptible to crack initiation. It induces deep residual compressive stress into the treated surface, increasing resistance to failure from fatigue and stress crack corrosion. As summarized by Don Roxby (appendix C), director of the Symbol Research Center, an international leader in the development of advanced symbology solutions for industrial, materials handling, and manufacturing environments,

> "Having failed to come up with a complete solution for this pressing issue, our organization was elated when we became aware of your work related to lasershot peening. The lasershot peen process provides the marking fidelity required to apply dense symbols to small parts without injecting risk. The process makes it possible to identify internal engine components such as aircraft turbine blades and a host of other difficult marking applications."

Metal Improvement Company, Inc. and the Lawrence Livermore National Laboratory are committed to implement the Lasershot^{sm} marking technology into the broadest possible range of applications.

Organization Data

13. **Chief Executive Officer** (corporate or university president, government research center director).

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14. **Contact person to handle all arrangements on exhibits, banquet and publicity.**

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15. To whom should reader inquiries about your product be directed?

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Appendices

A. List of additional developers of the Lasershot^{sm} Marking System.

B. Photographs of the Lasershot^{sm} Marking System in operation.

C. Letter of testimony (January 22, 2001) from RVSI Acuity CiMatrix Symbol Research Center, an international leader in the development of advanced symbology solutions for industrial, materials handling, and manufacturing environments.

D. Announcement of Lasershot^{sm} marking on the RVSI Acuity CiMatrix web site, http://www.rvsi.com/acuitycimatrix/rr-markb.html.

E. NASA News Release (January 8, 2001) describing the Materials International Space Station Experiment (MISSE) in which Lasershot^{sm} marked parts will participate. It will be the first science experiment on the Space Station and the parts will be carried up on Space Shuttle Mission STS-105 in late June 2001.

F. United States Patents 5,239,408 (August 24, 1993) and 5,689,363 (November 18, 1997) for the high average power, high beam quality laser technology required by Lasershot^{sm} marking. Patent applications have been filed for the Lasershot^{sm} marking technique as well as for the beam delivery system. All claims have now been allowed on the latter application and the patent will be issued shortly.

G. Video showing the marking of a gear with the Data Matrix symbol using Lasershot^{sm} Marking System. The multiple-shot matrix marking technique is used to inscribe the 18x18 identification symbol on the helicopter gear shown in the photographs of Appendix B. The 3-minute presentation on the CD-ROM is in Quicktime format. A VHS tape copy is also provided.

Appendix A

Additional developers of the Lasershot^{sm} marking process.

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FAX:	(316) 267-0412
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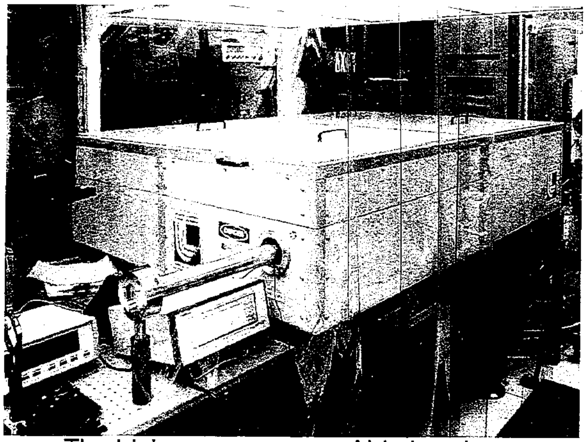
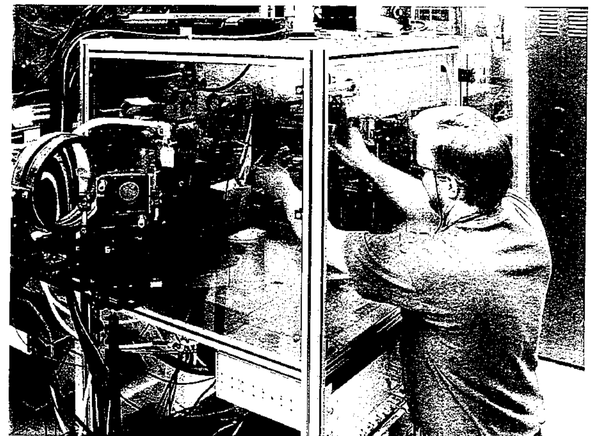
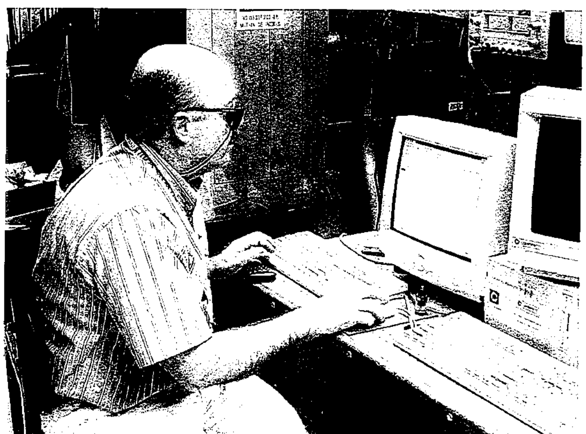
Appendix B



The high average power Nd:glass laser system used in the Lasershot^{sm} Marking System.



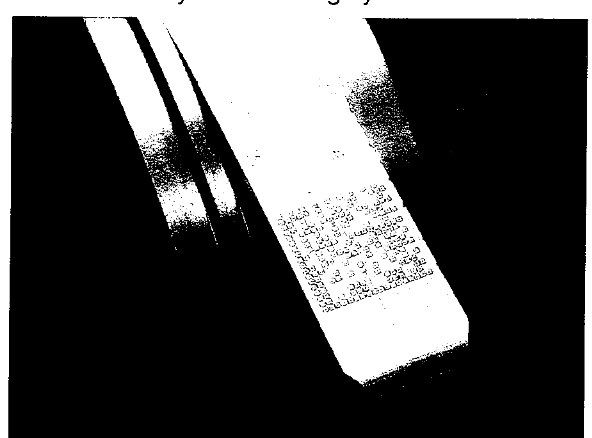
The peen marking treatment station. A patented optical beam delivery system provides accurate single pulse or multi-pulse marking and pattern control.



An automated robotic part handling system provides hands-off operation with high throughput processing.

The peen-marked parts can be easily read with the standard RVSI CiMatrix Data Matrix symbol reading system.

The identification reading process for the helicopter gear sample that was peen marked in the enclosed short video.



Close up view of the peen-marked Data Matrix applied to the sample steel gear.

Appendix C

Letter of testimony (January 22, 2001) from RVSI Acuity CiMatrix Symbol Research Center, an international leader in the development of advanced symbology solutions for industrial, materials handling, and manufacturing environments.

CiMatrix

January 22, 2001

In reply refer to: SRC01-009

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Tel: (925) 422-9009
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Attention: Lloyd Hackel

Subject: Markings on Mission –International Space Station – Experiment (MISSE)

Dear Lloyd,

As part of our Space Act Agreement with NASA, the Acuity CiMatrix Symbol Research Center (SRC) is developing safe marking methods that can be used to apply two-dimensional (2-D) symbols onto aerospace parts. Of particular interest has been the marking of safety critical parts that are subjected to harsh manufacturing, operational, and overhaul processes. Our challenge has been to find an intrusive marking process that will survive in the use environments without degrading the material properties of the part. While dot peening, engraving, micro-milling, laser engraving and other processes have been shown to survive under harsh conditions, they reduce the operational life of parts subjected to operational stresses. They can also introduce hazards into an otherwise safe program if applied incorrectly.

The SRC has successfully developed methods and means to safely cast symbols onto the surface of parts during manufacturing. However, the mold and cast marking method is generally limited to larger parts. Having failed to come up with a complete solution for this pressing issue, our organization was elated when we became aware of your work related to lasershot peening. The lasershot peen process provides the marking fidelity required to apply dense symbols to small parts without injecting risk. The process makes it possible to identify internal engine components such as aircraft turbine blades and a host of other difficult marking applications.

NASA is very interested in the process and recently added lasershot peening to its Data Matrix Direct Part Marking Standard (NASA-STD-026) and Handbook (NASA-HDBK-027). They, along with the DoD, are also in the process of conducting ground, flight, and in-orbit marking tests to certify its use in both current and future programs.

CiMatrix, Symbology Research Center, 4975 Bradford Drive NW, Suite 500, Huntsville, AL 35805 Tel: 205-830-8123 Fax: 205-895-0585

I think that I can safely extend the compliments of RSVI and the US Government to both you and your staff for the help and assistance you have provided us in evaluating this new and revolutionary marking process.

Respectfully,

D. L. Roxby

Donald L. Roxby
Director, Acuity CiMatrix Symbology Research Center
5000 Bradford Drive NW, Suite A
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Howes, Curtis – VP, Automatic Identification – RVSI
Schemenaur, James – President, Acuity CiMatrix
Schramm, Fred – NASA Technology Transfer Office

Correspondence File
Computer File: F:/CiMatrix/Letters/SRC01-008

Appendix D

Announcement of Lasershot^{sm} marking on the RVSI Acuity CiMatrix web site, http://www.rvsi.com/acuitycimatrix/rr-markb.html.

RVSI
Acuity CiMatrix
5 Shawmut Road, Canton, MA 02021 — 1-781-821-0830 (USA Only 1-800-646-6664)

RVSI Acuity CiMatrix Marking Bulletins

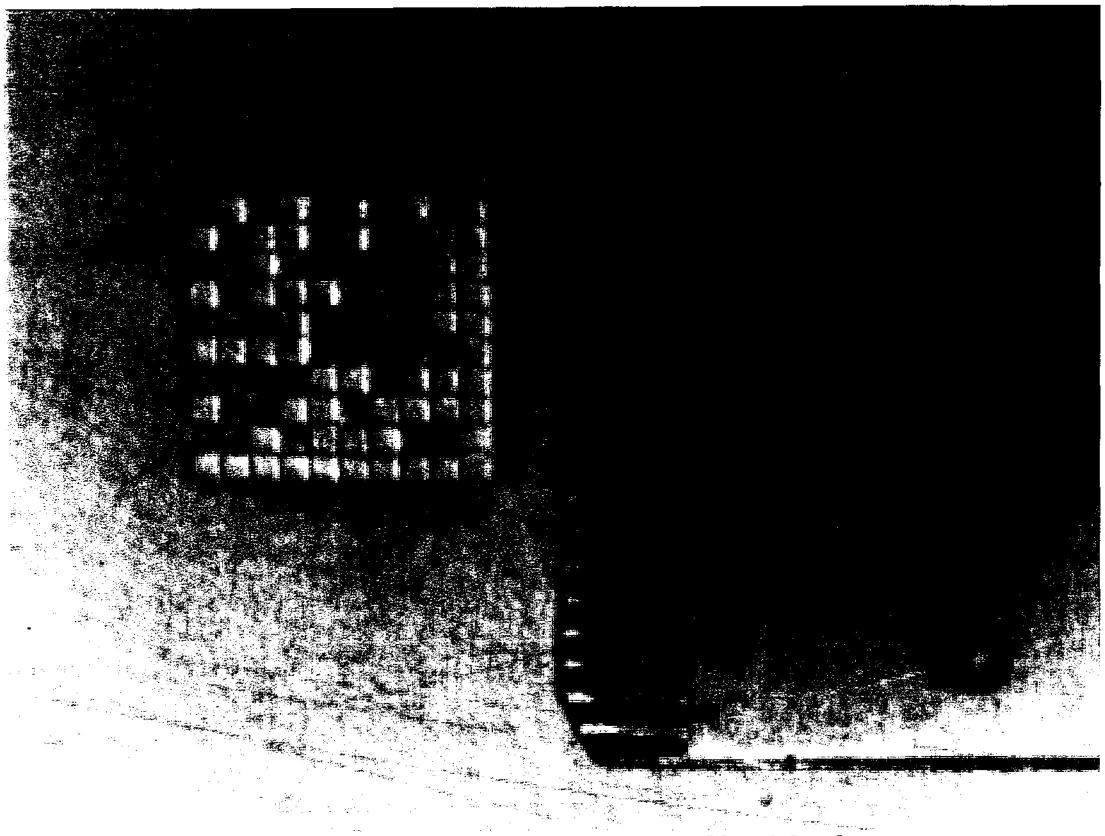
LaserShot Peening

LaserShot Peen? is a process developed to safely apply recessed identification markings to metal components. The technique involves the use of a laser peening system that impresses an image, generated in the near field spatial profile of the laser beam, onto the metal. The markings formed in this manner produce a residual compressive stress that is resistant to fatigue failure and stress corrosion cracking making the process highly advantageous for use in safety critical applications. Another appealing attribute of the process is it?s ability to produce symbol s that can be reduced in very small size, allowing the identification of parts previously to small to identify with mechanical peening means.

In the laser peening process a thin layer of absorptive material is placed over the area to be peened and a thin, approximately 1 mm thick layer of fluid is flowed over the absorption layer. A high intensity laser with fluence of approximately 100 J/cm2 and pulse duration of 15 ns, illuminates and ablates material from the absorption layer, creating an intense pressure pulse that initially is confined by the water layer. This pressure creates a shock wave that strains the metal surface in a two-dimensional pattern directly correlated to the laser intensity profile at the metal surface. By creating a desired pattern upstream in the light field and imaging this pattern onto the metal surface, the entire desired pattern is pressure printed with a single laser pulse. By employing spatial light modulation of the near field beam and subsequent imaging of this pattern onto the metal, a completely new Data Matrix? symbol can be created with each laser pulse. Essentially any two or three-dimensional pattern can be printed including the 1-D (linear bar codes), 2-D symbols and human-readable characters.

A breakthrough in laser technology employing a Nd:glass laser and a wavefront correction technology called phase conjugation now enables the building of a laser system that can operate a 6 pulses per second with output energy of up to 100J. This represents a fundamental capability of peen marking 6 complete data matrices per second.

LaserShot peen marking can be used on any non-brittle material that undergoes plastic strain upon reaching its stress yield point. It will not work well on materials that fracture such as glass. The process can be combined with an overall shot peening or LaserShot peening of the surface to provide excellent protection against fatigue failure and stress corrosion cracking.



LaserShot Peen Marking Applied to Metal Surface

For more information related to laser bonding for high heat applications, contact the SRC or:

Lawrence Livermore National Laboratory
Mailcode: L-487
7000 East Ave.
Livermore, CA 94550-9234
Tel: (925) 422-9009
Fax: (925) 423-9242
E-mail: hackel1@llnl.gov
Web Site: http://www.llnl.gov/str/Hackel.html

Metal Improvement Company, Inc.
10 Forest Avenue
Paramus, NJ 07652
Tel: (201) 843-7800
Fax: (201) 843-3460
E-mail: METALIMP@ix.netcom.com
Web Sites: http://www.metalimprovement.com

The Symbology Research Center is the most advanced 2-D symbology R&D laboratory in the world, maintaining the countries most comprehensive materials marking database. The center maintains a close relationship with NASA to further develop this 2-D technology. The SRC, through RVSI, holds more than a hundred patents related to 2-D and 3-D technology and has developed, enhanced and tested over 40 compressed symbology marking methods. Our consulting service can usually solve your most difficult machine-readable part marking or code reading problems via the use of the Data Matrix symbology. Any government or commercial entity can request assistance on a specific product identification problem by submitting a Problem Statement through the

Marshall Space Flight Center Technology Utilization Office or directly through the SRC

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Appendix E

NASA News Release (January 8, 2001) describing the Materials International Space Station Experiment (MISSE) in which Lasershot[sm] marked parts will participate. It will be the first science experiment on the Space Station and the parts will be carried up on Space Shuttle Mission STS-105 in late June 2001.

News Release

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-0001

Marny Skora
Langley Research Center, Hampton, VA
(757) 864-6121
m.m.skora@larc.nasa.gov

For Release: January 8, 2001

RELEASE NO. 01-003

NASA Langley Forecast: What's to come in 2001

Researchers at NASA's Langley Research Center in Hampton, VA, are working to improve today's aircraft, to develop concepts for future aircraft, to support the nation's space program and to develop technology for advanced space transportation systems, for small spacecraft and space instruments. Here are a few of the things we invite you to explore in the first half of 2001:

• NASA "soups-up" small aircraft to test new transportation concepts

NASA is purchasing two of the latest and greatest general aviation aircraft in a multi-year effort to prove that a transportation system based on 4-8 passenger aircraft is a viable alternative to flying on a commercial airliner or driving a car for trips from 150 to 1,000 miles. The new aircraft, themselves the product of NASA research, will be "souped up" by NASA Langley researchers to include technologies still in the experimental stage, like synthetic vision for safe flight at night and in near all-weather conditions. The first of the two aircraft is scheduled for arrival in late **January**. Contact Keith Henry, 757-864-6120.

• Materials experiment first science for Space Station

Langley's MISSE (Materials International Space Station Experiment) will be the first science experiment on the Station. The experiments will investigate the effects of radiation and other environments on approximately 1,500 materials housed in passive experiment containers that look like suitcases. The suitcases, assembled in clean rooms at Langley Research Center, will be shipped to Kennedy Space Center in **February** for launch on STS-105 in late June.
Contact Ivelisse Gilman, 757-864-5036.

• 2001, a Mars Odyssey

The Mars Odyssey spacecraft is set for launch **April 7** and is scheduled to arrive at Mars in late October. NASA Langley experts are responsible for the 70-day aerobraking -- gradually dipping the spacecraft into the planet's upper atmosphere -- to reach a final Mars orbit.
Contact Ivelisse Gilman, 757-864-5036.

- more -

• NASA research pilots set out on a turbulent course

Using a 757 aircraft outfitted as a "flying laboratory," NASA Langley crews will hunt out turbulence -- the kind of rough air that most airliners try to avoid and the greatest cause of airline injuries. NASA is trying to come up with technologies to detect, warn of and minimize turbulence, a phenomenon that costs airlines at least $100 million a year. Depending on the weather, flights are planned for the **April-May** timeframe.
Contact Kathy Barnstorff, 757-864-9886.

• Student teams challenged to build best robot

The FIRST Robotics Competition, a national engineering contest, immerses high school students in the exciting world of engineering. Teaming with engineers from businesses and universities, students get a hands-on, inside look at the engineering profession. In six intense weeks, the student-engineer teams brainstorm, design, construct and test their robots. Local teams will compete in a spirited, no-holds-barred tournament in **May** in Richmond.
Contact Kim Land, 757-864-9885.

• Flight at one mile per second is only the beginning

Managed by NASA Langley Research Center, the Hyper-X program is a series of experimental flights to expand aeronautics and develop new technologies for space access. When the X-43 flies in **May**, it will be the first time a non-rocket, air-breathing engine has powered a vehicle in flight at hypersonic speeds -- about one mile a second or approximately 3,600 mph.
Contact Chris Rink, 757-864-6786.

• NASA -- working to ensure that flying remains the safest way to travel

The 757 flying lab will also test a revolutionary cockpit display system, being developed to give pilots a clear electronic picture of what's outside their windows -- no matter what the weather or time of day. The system is a kind of synthetic vision that would address limited visibility -- the single largest contributing factor in fatal worldwide airline and general aviation crashes. Test flights are now scheduled for **June**.
Contact Kathy Barnstorff, 757-864-9886

• This year from Russia, a NASA Langley SAGE

Our understanding of natural and man-made atmospheric processes will be enhanced by a satellite sensor designed to provide accurate, long-term measurements of aerosols, ozone, water vapor, and other important trace gases in the upper troposphere and stratosphere. Several flights of the Stratospheric Aerosol and Gas Experiment (SAGE) III instrument are planned, including a flight aboard a Russian Meteor-3M platform this **summer**.
Contact Chris Rink, 757-864-6786.

- end -

Appendix F

United States Patents 5,239,408 (August 24, 1993) and 5,689,363 (November 18, 1997) for the high average power, high beam quality laser technology required by Lasershot^{sm} marking. Patent applications have been filed for the Lasershot^{sm} marking technique as well as for the beam delivery system. All claims have now been allowed on the latter application and the patent will be issued shortly.

US005689363A

United States Patent [19]

Dane et al.

[11] Patent Number: 5,689,363

[45] Date of Patent: Nov. 18, 1997

[54] **LONG-PULSE-WIDTH NARROW-BANDWIDTH SOLID STATE LASER**

[75] Inventors: **C. Brent Dane; Lloyd A. Hackel**, both of Livermore, Calif.

[73] Assignee: **The Regents of the University of California**, Oakland, Calif.

[21] Appl. No.: **489,402**

[22] Filed: **Jun. 12, 1995**

[51] **Int. Cl.**^{6} **H01S 3/10**; H01S 3/098; H01S 3/08; H01S 3/23

[52] **U.S. Cl.** **359/334**; 359/338; 359/346; 372/21; 372/93

[58] **Field of Search** 359/334, 338, 359/346, 349; 372/21, 93

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,757,268	7/1988	Abrams et al.	330/4.3
4,943,782	7/1990	Stephens et al.	359/348
5,239,408	8/1993	Hackel et al.	359/338
5,260,954	11/1993	Dane et al.	372/25
5,285,310	2/1994	Miller et al.	359/338

OTHER PUBLICATIONS

Dane et al, CLRO '95, May 22, 1995, vol. 455, p. 1; abst. only herewith.

Dane et al., IEEE J.Q.E., vol. 31, #1, pp. 148–163, Jan. 1995,; abst. only herewith.

Dane et al, Proc. IEEE, Int. Soc. Opt. Eng. vol. 1626, pp. 308–316, 1992; abst. only herewith.

Hackel et al, Int. J. Nonlinear Opt. Phys., vol. 2, #1, pp. 171–185, Jan. 1993; abst. only herewith.

Phillips et al, Appl. Opt., vol. 32, #36, Dec. 20, 1993, pp. 7408–7417; abst. only herewith.

Seidel et al, Appl. Opt., vol. 32, #36, pp. 7408–7417, Dec. 20, 1994; abst. only herewith.

Aniheev et al, Soc. Journ. Quant. Elect., vol. 20, #3, pp. 235–236, Mar. 1990; abst. only herewith.

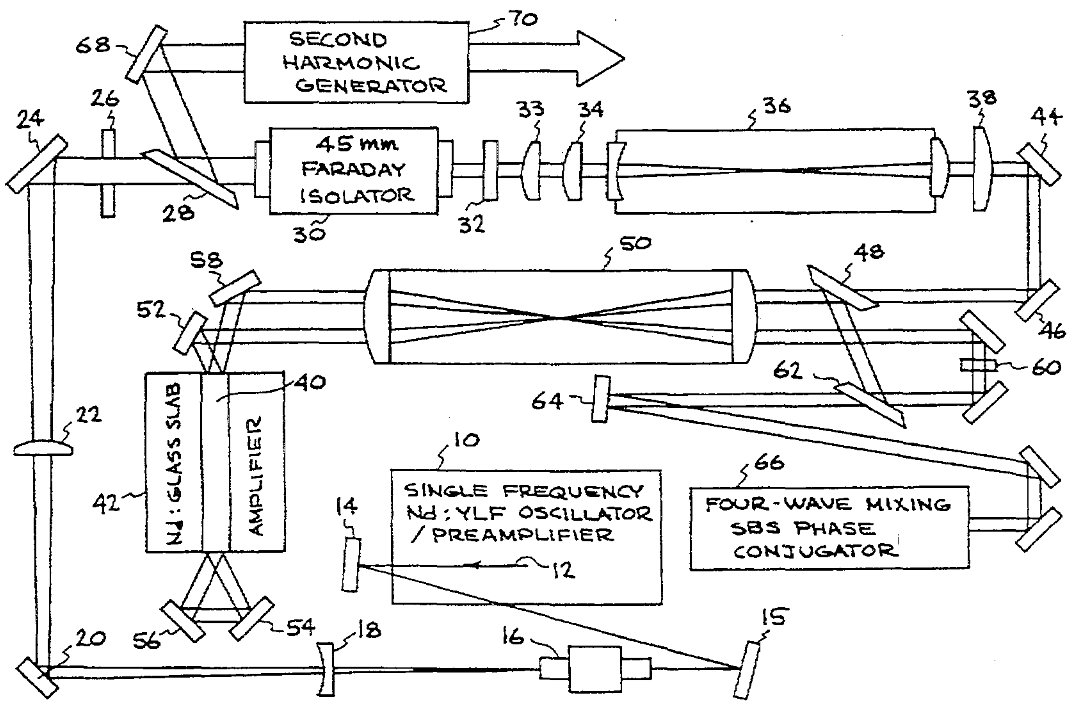
Primary Examiner—Nelson Moskowitz

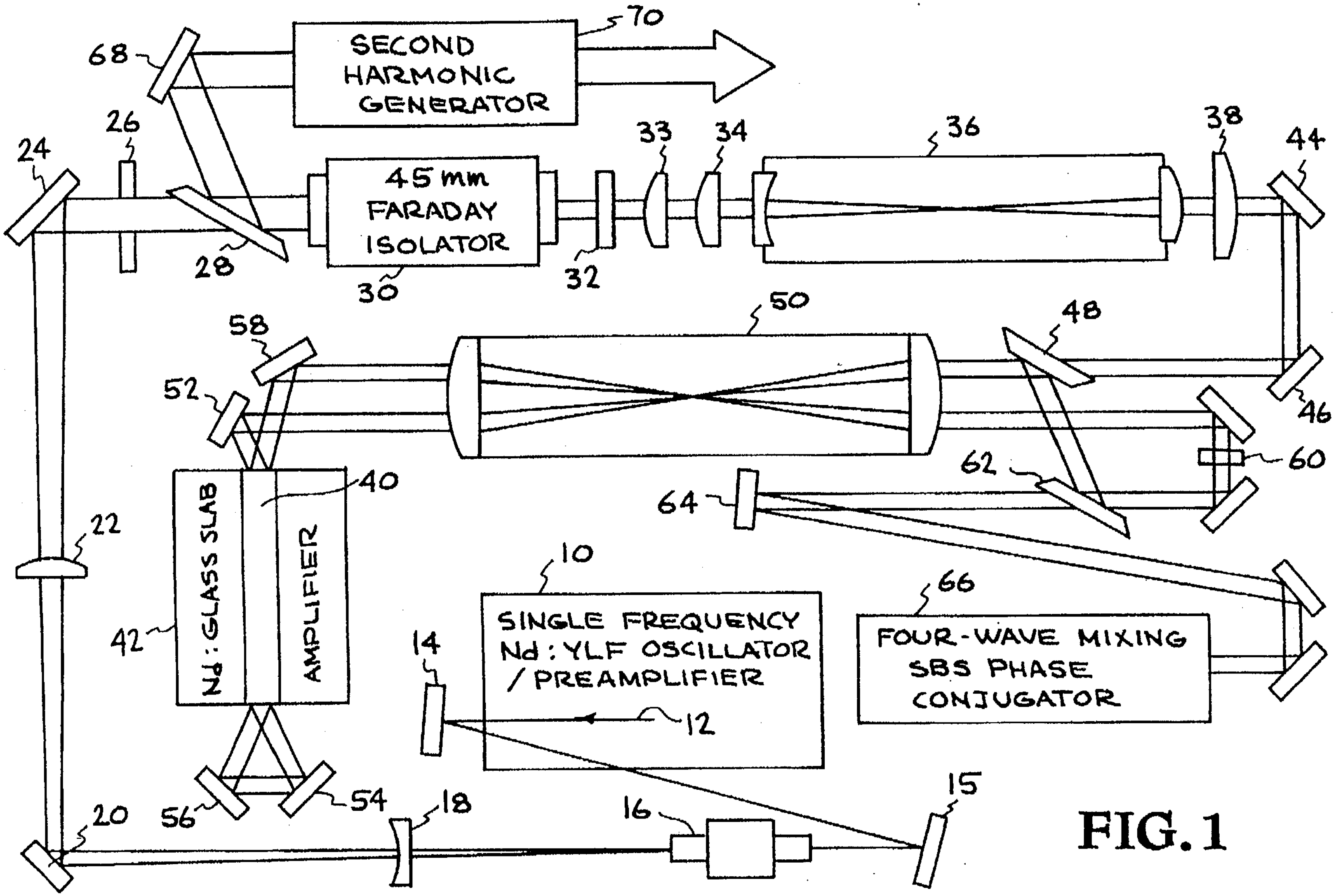
Attorney, Agent, or Firm—Henry P. Sartorio; John P. Wooldridge

[57] **ABSTRACT**

A long pulse laser system emits 500–1000 ns quasi-rectangular pulses at 527 nm with near diffraction-limited divergence and near transform-limited bandwidth. The system consists of one or more flashlamp-pumped Nd:glass zig-zag amplifiers, a very low threshold stimulated-Brillouin-scattering (SBS) phase conjugator system, and a free-running single frequency Nd:YLF master oscillator. Completely passive polarization switching provides eight amplifier gain passes. Multiple frequency output can be generated by using SBS cells having different pressures of a gaseous SBS medium or different SBS materials. This long pulse, low divergence, narrow-bandwidth, multi-frequency output laser system is ideally suited for use as an illuminator for long range speckle imaging applications. Because of its high average power and high beam quality, this system has application in any process which would benefit from a long pulse format, including material processing and medical applications.

36 Claims, 3 Drawing Sheets

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SECOND HARMONIC GENERATOR
68
26
24
28
45 mm FARADAY ISOLATOR
30
32
33
34
36
38
44
50
58
48
52
46
60
62
64
40
Nd : GLASS SLAB
AMPLIFIER
42
22
10
66
SINGLE FREQUENCY Nd : YLF OSCILLATOR / PREAMPLIFIER
12
FOUR-WAVE MIXING SBS PHASE CONJUGATOR
14
15
16
18
20
54
56

FIG. 1

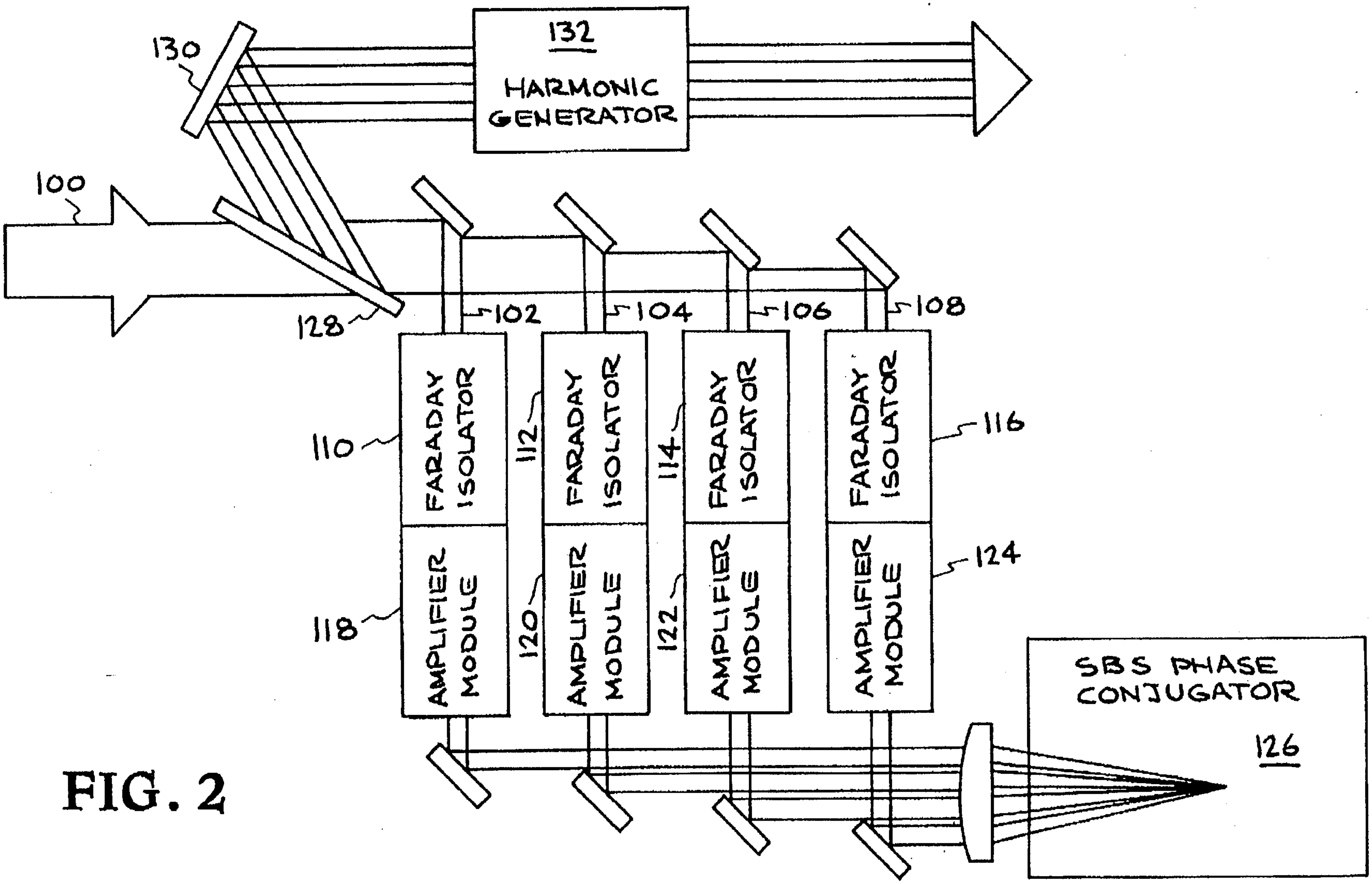
132
HARMONIC GENERATOR
130
100
128
102
104
106
108
110
112
114
116
FARADAY ISOLATOR
FARADAY ISOLATOR
FARADAY ISOLATOR
FARADAY ISOLATOR
118
120
122
124
AMPLIFIER MODULE
AMPLIFIER MODULE
AMPLIFIER MODULE
AMPLIFIER MODULE
SBS PHASE CONJUGATOR
126

FIG. 2

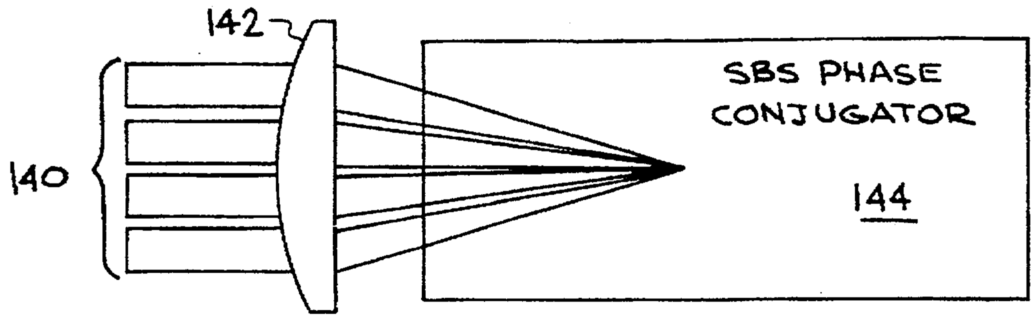

FIG. 3A

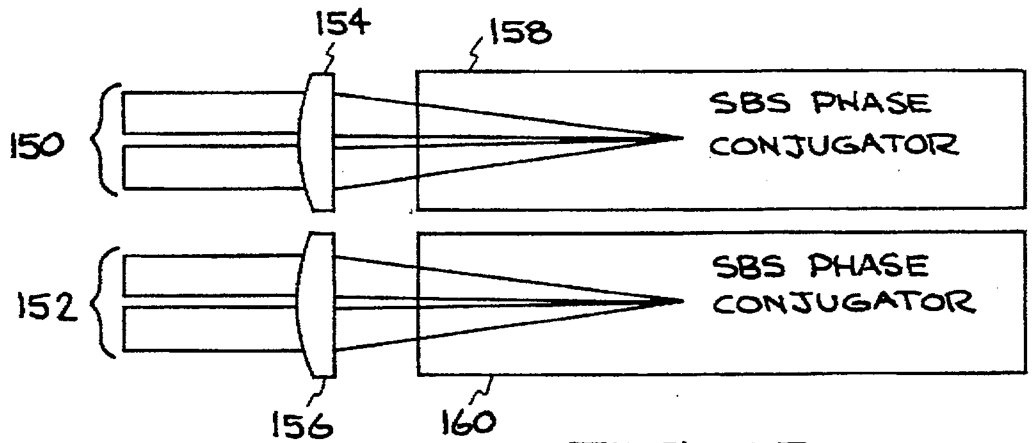

FIG. 3B

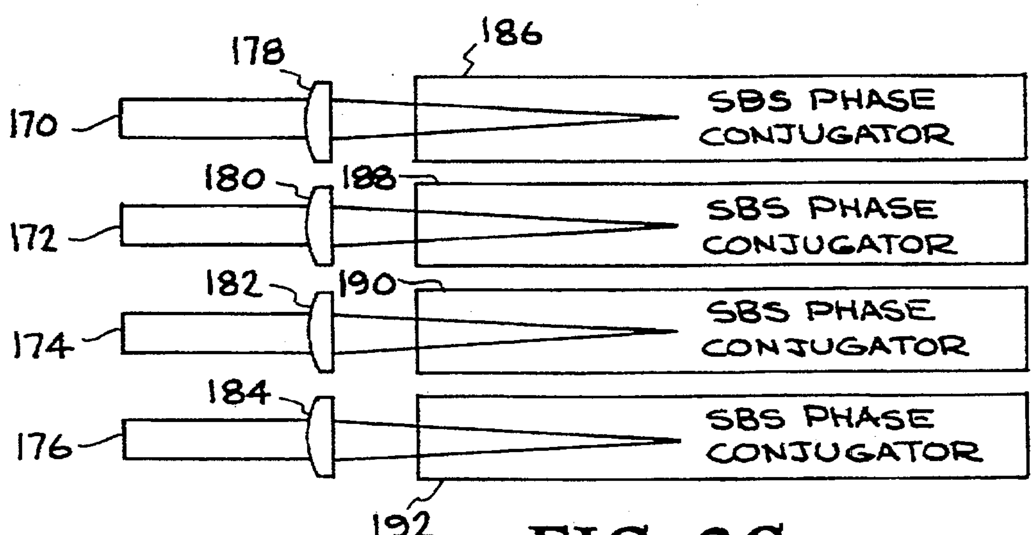

FIG. 3C

LONG-PULSE-WIDTH NARROW-BANDWIDTH SOLID STATE LASER

The United States Government has rights in this invention pursuant to Contract No. W-7405-ENG-48 between the United States Department of Energy and the University of California for the operation of Lawrence Livermore National Laboratory.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to solid state laser systems, and more specifically, to the efficient operation of solid state laser systems to produce long pulse-width, narrow-bandwidth outputs.

2. Description of Related Art

The efficient operation of solid state laser systems with long pulse-widths is a challenging problem. Typical Q-switched laser systems operate with pulse widths of 5–30 ns. Free running long pulse operation of a solid state laser results in a long train of pulses caused by the phenomenon of relaxation oscillation (spiking) with only a small amount of the total energy in each pulse. A number of approaches have been made to solve the long pulse problem including closed-loop variable Q-switch, open-loop variable Q-switch, saturable absorber Q-switches and the amplification of a single relaxation oscillation pulse. The first three methods typically exhibit very poor pulse to pulse stability in pulse duration, shape, and energy, and they have only been demonstrated at sub-mJ output energies. The amplification of a single relaxation oscillation pulse has been the most successful with the recent report of 1.1 J from a single laser aperture in a relatively short 100 ns pulse. The output pulse in this work maintained the approximately Gaussian shape of the input pulse; however, for most long pulse laser applications, a constant-power near-rectangular pulse-shape is desired. It is desirable to naturally produce these near-rectangular pulses with very high efficiency.

Long-pulse oscillators emitting near-rectangular pulses have been demonstrated by suppressing the relaxation-oscillation behavior (spiking) typical of solid state lasers. This has been accomplished by actively varying the intracavity loss during the laser pulse with either closed-loop feedback of the output power or with a pre-programmed temporal shape. In both cases, pulse widths of up to 600 ns were achieved. However, the sensitivity and bandwidth required for these control schemes are often difficult to achieve even in a carefully controlled laboratory environment. Long pulses have also been generated with passive control using an intracavity saturable absorber. Pulse widths of up to 500 ns have been demonstrated but with a peaked temporal profile, a large shot-to-shot pulsewidth variation (100 ns RMS), and a pulse energy of only 0.2 mJ.

The large amount of gain required for a high energy amplifier system requires that the gain medium be multi-passed for efficient extraction. However, the physical length of a 0.5–1 μs laser pulse (150–300 m) makes a multi-pass system using conventional electro-optical polarization beam switching impossible. It is desirable to design a high energy amplifier system having multi-pass capability, where the amplifier system uses a single aperture.

For applications in laser illumination and/or high average power operation, high beam-quality with low output beam divergence is critically required. No previous report of a long pulse laser system has been made that successfully incorporates wave-front correction such as that achieved with simulated-Brillouin-scattering (SBS) due to the difficulty in driving the nonlinear process above threshold during the long laser extraction pulse. It is desirable to provide a high energy amplifier system that both reduces the power threshold and produces a stable, long coherence-length output.

In illumination applications which use speckle imaging for high resolution imaging through turbulent atmosphere, at least two and up to four discrete laser frequencies with relative shifts of approximately 5 MHz must be simultaneously projected onto the target of interest. The approach of the past has been to take the output of a laser system, break it into separate beams, use either acousto or electro-optical modulation to induce the frequency shifts, and then to use a complex optical train to recombine the beams to be precisely collinear. It is desirable to provide a system which generates these frequencies inside the laser itself, where the beams are automatically assured to be exactly collinear, regardless of small alignment perturbations in the various components of the amplification beam trains.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a long-pulse-width, narrow-bandwidth solid state laser.

It is another object of the present invention to provide an amplification technique that naturally produces near-rectangular pulses with very high efficiency.

It is another object of the invention to provide a system that uses passive polarization rotation by a large aperture Faraday rotator and quartz rotators to provide eight pass amplification through a single amplifier aperture.

A further object of the invention is to incorporate a simulated-Brillouin-scattering (SBS) system, using a multi-passed Brillouin enhanced geometry, into the design of an optical amplifier to both reduce the power threshold and to produce a stable, long coherence-length output.

Another object of the invention is to take the output of a laser master oscillator system, break it into a specific number of separate beams, direct the separate beams through separate multipass amplifiers and reflect them at the mid-point in amplification from separate SBS phase conjugators where separate frequency shifts are generated for each beam in an SBS process and where the beams are automatically assured to be collinear, regardless of small alignment perturbations in the various components of the amplification beam trains.

The invention is a long pulse laser system that emits 500–1000 ns quasi-rectangular pulses at 527 nm with near diffraction-limited divergence and near transform-limited bandwidth. The system consists of one or more flashlamp-pumped Nd:glass zig-zag amplifiers, a very low threshold SBS phase conjugator system, and a free-running single frequency Nd:YLF master oscillator from which we use the exponentially rising edge of a relaxation oscillation pulse. Completely passive polarization switching provides eight amplifier gain passes. Multiple frequency output can be generated by using SBS cells having different pressures of a gaseous SBS medium or different SBS materials. This laser system produces a long pulse, low divergence, narrow-bandwidth, multiple single-frequency outputs. It is useful as an illuminator for long range speckle imaging applications. Because of its high average power and high beam quality, this system also has application in any process which would require a long pulse format, including material processing, medical applications and pumping another laser amplifier such as $Ti:Al_2O_3$ (Titanium sapphire).

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows the amplifier system having a simulated-Brillouin-scattering (SBS) phase conjugated architecture.

FIG. 2 shows a multifrequency amplifier system having an SBS phase conjugated structure.

FIG. 3A shows a single beam SBS phase conjugated design.

FIG. 3B shows an SBS phase conjugated design having two co-propagating beams.

FIG. 3C shows an SBS phase conjugated design having four co-propagating beams.

DETAILED DESCRIPTION OF THE INVENTION

In the invention, the saturation of a leading edge of a free-running oscillator results in a quasi-rectangular output pulse. The amplitude of the output is a function of only the exponential time constant of the oscillator build-up; therefore, increasing gain in the amplifier does not increase the peak power, but extends the length of the pulse. This behavior can be recognized by reviewing the equations for the time dependence of the output power. For a system with time varying gain G(t), the output power $P_o(t)$ depends on the input power Pi(t) in the following way;

$$P_o(t)=P_i(t)e^{G(t)}.$$

Take the derivative of this equation and set $dP_o(t)/dt=0$ for constant output power and recognize that the time constant z can be defined by the relationship;

$$\tau=1/(dG(t)/dt)-(P_o n/E_{sat}A);$$

where n is the number of amplifier passes, Esat is the saturation fluence of the gain media and A is the cross-sectional area of the amplifier and n is the number of amplifier passes. Rearranging the resulting equation and integrating both sides results in

$$Pi(t)=Ce^{t/\tau}$$

where C is a constant of integration. This result clearly shows that to get a constant output pulse power requires an exponentially rising input pulse.

The oscillator is allowed to build up at a slow rate until the simulated-Brillouin-scattering (SBS) phase conjugator reaches threshold. The build up rate is then increased to the level required for the desired amplifier output level. This yields the lowest possible SBS threshold. The use of multi-passed Brillouin enhanced four wave mixing phase conjugation provides both the very low threshold SBS required for generation of long pulses as well as frequency and phase stability for Stokes return extending over many acoustic relaxation times during the long pulse.

FIG. 1 is a schematic diagram of an embodiment of a long-pulse-width, narrow-bandwidth, solid state laser system according to the present invention. The Figure shows an oscillator/preamplifier **10** comprising, e.g., a single frequency Nd:YLF laser oscillator or preamplifier. Oscillator/preamplifier **10** produces single frequency laser beam **12**. In the Nd:YLF embodiment, beam **12** has a wavelength of 1054 nm, at 240 ns FWHM and typically 60 mJ of power. Upon exiting oscillator/preamplifier **10**, beam **12** is polarized horizontally, i.e., parallel to the plane of the paper of FIG. **1**. Beam **12** maintains this polarization as it reflects from turning mirrors **14** and **15**, passes through Faraday isolator **16** and negative lens **18**, reflects from mirror **20**, passes through positive collimating lens **22**, reflects from mirror **24** and is masked by input mask **26**. Polarizing beamsplitter **28** is oriented to transmit P-polarization, and thus, transmits horizontally polarized beam **12**.

The directions of rotation of 45° Faraday isolator **30** and 45° quartz rotator **32** cancel each other in the input direction such that the beam which exits remains horizontally polarized (FIG. **1**). Beam conditioning optics **33** and **34**, anamorphic relay telescope **36** and collimating lens **38** prepare the beam size to fit the required aperture **40** of amplifier **42**. Beam **12** reflects from mirrors **44** and **46** and transmits through polarizing beamsplitter **48** which is configured to transmit P-polarization and reflect S-polarization. The transmitter beam is relayed by 1:1 relay telescope **50** to a two-pass optical axis comprising mirrors **52**, **54**, **56** and **58**. The amplifier **42** is place on axis with this two-pass optical axis. After passing through relay telescope **50** again, the polarization of beam **12** is rotated 90° by quartz rotator **60** to the vertical plane, i.e., perpendicular with respect to the plane of the paper. Beam **12** is then reflected by polarizing beamsplitter **62** to be re-injected into the amplification system by polarizing beamsplitter **48**.

After two more amplification passes, the polarization of beam **12** (FIG. **1**) is again rotated 90° allowing transmission through beamsplitter **62**, reflection from mirror **64** and entrance into Four-wave mixing SBS phase conjugator **66**, which reverses the phase of beam **12**. Upon reversal of direction, horizontally polarized beam **12** undergoes 4 more amplification passes and propagating through polarizing beamsplitter **48**, collimating lens **38**, anamorphic relay telescope **36**, conditioning optics **33**, **34**, and Faraday isolator **30**, beam **12** exits the system at polarizing beamsplitter **28**, which is configured to reflect S-polarization. Mirror **68** directs beam **12** through second harmonic generator **70**. If the preamplifier **10** produces a pulse at 60 mJ, 240 ns FWHM and 105.4 µm, the output from second harmonic generator will be a pulse of about 16 J, at greater than 500 ns and 527 nm wavelength.

The 45 degree Faraday and quartz rotator set result in a totally passively switched beam train. The beam enters the amplifier system from the oscillator through the anamorphic telescope which takes it from a square 25×25 mm size to the 8×120 mm required by the glass amplifier aperture. In this design, the output passes back through the same telescope, restoring the 25×25 mm square beam shape. The input beam enters the regenerative amplifier ring in p-polarization through a polarizing beamsplitter, and undergoes two gain passes. The polarization is then rotated 90 degrees by the quartz rotator and it now reflects from the same beamsplitter in s-polarization and undergoes two more gain passes. When the polarization is returned to the original p-state after the second pass through the rotator the beam is coupled out through a polarizing beamsplitter in the ring and directed into the SBS four-wave mixing conjugator. The reflected beam from the conjugator retraces the path of the input beam, resulting in four more gain passes for a total of eight. The polarization rotation of the 45 degree Faraday rotator and the 45 degree quartz rotator canceled each other in the input direction but now, in the output direction, they add resulting in a full 90 degree rotation, and the amplified beam is reflected off the first polarizing beamsplitter and enters the doubler.

FIG. **2** depicts a conceptual schematic of a multi-frequency version of the system. In this design, the oscillator input beam **100** is partitioned into 4 sub-beams **102**, **104**, **106** and **108**, and directed through 4 separate Faraday isolators **110**, **112**, **114** and **116**, and 4 separate amplifier modules **118**, **120**, **122** and **124**. After four gain passes, the beams are then recombined in an SBS phase conjugator system **126**. The four beams return on their respective input paths and are reflected by polarizing beamsplitter **128** to mirror **130** and through second harmonic generator **132**. Using the same preamplifier specifications of the embodiment of FIG. **1** results in about 65 J at 527 nm and 600 ns.

FIGS. 3A–3C show schematically three of the many possible configurations for this system. In FIG. **3A**, combined input beam **140** comprising four beams are focused by lens **142** into an SBS phase conjugator system **144**. In FIG. **3B**, combined input beam **150** and **152**, each comprising two beams, are each focused by separate lenses **154**, **156**, into two separate SBS phase conjugator systems **158**, **160**. In FIG. 3C, four input beams, **170**, **172**, **174** and **176**, are focused by lenses **178**, **180**, **182** and **184**, into SBS phase conjugator systems, **186**, **188**, **190** and **192**. The separate cells have either different SBS media, or the same SBS medium at different pressures, in order to vary the Stokes shift for each channel, and hence produce relative frequency shifts between two or more of the beams. In the present invention, the amplifier output can be varied from a single coherent high energy beam to multiple frequency-shifted beams. Since the multiple beams arise from a single oscillator beam, they automatically exhibit exact spatial overlap in the far field (collinearity) independent of alignment variations in the amplifier modules.

This laser amplifier extraction system allows the efficient generation of up to microsecond laser pulses by the amplification of the exponentially-rising leading edge of a free-running oscillator pulse. The output pulses are near-rectangular in shape, 600 ns in duration, and exhibit a measured coherence length of greater than 60 m. Very low threshold SBS phase conjugation using Brillouin-enhanced four-wave-mixing results in high shot-to-shot and long-term pointing stability as well as near-diffraction-limited output divergence at the full 3 Hz operating pulse-repetition-frequency (PRF).

In laser illumination applications such as long-range coherent radar or high-resolution speckle imaging, a narrow-bandwidth high energy output is required with pulse-widths in the range of 500 ns to 1 µs. These applications also benefit from the near constant output power provided by a quasi-rectangular temporal pulse-shape. The optimization of non-linear frequency conversion processes such as harmonic generation or the pumping of an optical parametric oscillator (OPO) also benefits from this pulse-shape. In addition to its use as a laser illuminator, the efficient operation of a high energy/pulse, high average power, long-pulse, solid-state laser system provides the potential for other applications in which the lower peak power improves radiation coupling and raises the optical damage threshold of materials. Examples include laser cutting and surface treatment, biological tissue treatment, as well as pumping other solid state storage lasers such as Ti:sapphire.

The energy per pulse requirements of a long range illuminator make a master-oscillator power-amplifier (MOPA) the most practical laser architecture. The design goal for the laser amplifier output that is presented here was >30 J/pulse at 1 µm. The large amount of amplification required to reach this energy from a low-energy injected oscillator pulse leads to severe temporal distortion of the input pulse-shape due to amplifier gain saturation during efficient optical extraction. For this reason, the near-rectangular output of previously reported long-pulse oscillators is not suitable as an injection source. It has been recognized, however, that the smooth temporal profile of a relaxation-oscillation pulse emitted by a free-running solid state laser suffers much less pulse-width distortion when amplified. Applying this concept, 1.1 J in a 110 ns pulse has been demonstrated from a single amplifier aperture which was then frequency-doubled to 520 mJ at 532 nm. The temporal profile remained, however near-Gaussian in shape.

This long-pulse laser scheme also relies on the amplification of the output of a free-running master oscillator. However, only the leading edge of the pulse is used. The measured width of the relaxation-oscillation spike does not determine the width of the amplified output pulse. The amplification of the leading edge of the input pulse gives rise to a quasi-constant output power, the magnitude of which is dependent only on the exponential time-constant of the rising edge. The power, and hence pulse duration, may be tailored to a desired level by adjusting the optical build-up time in the oscillator. The incorporation of very low threshold SBS phase conjugation provides near-diffraction-limited divergence and the output pulses can be frequency-doubled to 527 nm with greater than 50% total external conversion efficiency. This results in a laser system with 600 ns full-width-half maximum (FWHM) output pulse duration with a near-rectangular temporal profile, 16 J/pulse at 527 nm, and a maximum pulse-repetition-frequency (PRF) of 3 Hz. The output pulses have a measured coherence length of greater than 60 m. These demonstrated performance specifications exceed previously reported long-pulse green laser output by 5 times in duration, 30 times in pulse energy, and 18 times in average power from a single amplifier aperture. This is also the first demonstration of narrow-bandwidth SBS phase conjugation in a long-pulse, long-coherence-length laser amplifier system. Using the same laser system, pulses of almost 1 µs in duration were also amplified with equal output energy at 1053 nm. These were not doubled, however, since the design point of the second harmonic converter was for 600 ns pulses.

Changes and modifications in the specifically described embodiments can be carried out without departing from the scope of the invention, which is intended to be limited by the scope of the appended claims.

We claim:

1. An apparatus for producing a long-pulse-width, narrow-bandwidth, near diffraction limited quality output beam, comprising:

means for producing a polarized low power laser beam with an exponentially rising leading edge having a time constant τ determined from the formula

$$\tau=1/(dG(t)/dt)-(P_{o}n/E_{sat}A);$$

at least one optical amplifier;

means for providing multiple amplification passes of said polarized low power laser beam, said multiple amplification passes propagating through said at least one optical amplifier to produce at least one amplified beam with nearly constant output power determined by said time constant of said exponentially rising leading edge of said polarized low power laser beam;

means for reversing the phase of said polarized low power laser beam and its propagation direction after half of said multiple amplification passes through said at least one optical amplifier, said reversing means including stimulated-Brillouin-scattering (SBS), wherein said amplified beam retraces its path and relative polarization through said at least one optical amplifier; and

means for converting said at least one amplified beam into at least one output beam by passively switching the polarization of said at least one amplified beam.

2. The apparatus of claim **1**, wherein said means for producing a polarized low power laser beam with an exponentially rising leading edge comprise a laser master oscil-

lator activated by a pulsed source and operated in a free running output mode.

3. The apparatus of claim 2, wherein said laser master oscillator comprises a transmissive Pockels cell, wherein the rate of rise of said exponentially rising leading edge is modified by means of electronically changing the amount of polarization rotation generated by said transmissive Pockels cell within said laser master oscillator to produce first a slowly rising leading edge to allow the SBS process to reach threshold, wherein then said Pockels cell is deactivated to achieve a faster rising edge to achieve a desired output power.

4. The apparatus of claim 1, wherein said means for providing multiple amplification passes of said polarized low power laser beam include means for providing 8 amplification passes through said at least one optical amplifier to produce at least one amplified beam with nearly constant output power, wherein said means for reversing the phase of said polarized low power laser beam and its propagation direction comprise a phase conjugator.

5. The apparatus of claim 1, wherein said means for reversing the phase of said polarized low power laser beam and its propagation direction comprise a phase conjugator configured in a ring geometry with at least three focal spots, wherein said phase conjugator is placed at the physical mid-point of said multiple amplification passes, wherein said phase conjugator is setup in a 4 wave mixing stimulated Brillouin scattering (SBS) configuration to provide the reduced SBS threshold required for long pulse operation while generating and maintaining, narrow bandwidth, high beam spatial quality and stable beam pointing of said long-pulse-width, narrow-bandwidth, near diffraction limited quality output beam.

6. The apparatus of claim 1, wherein said means for producing a polarized laser beam are selected from a group consisting of a solid state laser master oscillator and a solid state laser preamplifier, wherein said producing means are operated in the free running mode.

7. The apparatus of claim 1, wherein said means for producing a polarized laser beam are selected from a group consisting of a single frequency Nd:YLF laser oscillator and a single frequency Nd:YLF preamplifier, wherein said producing means are operated in the free running mode.

8. The apparatus of claim 6, further comprising a first Faraday isolator to prevent back reflections from entering said means for producing a polarized laser beam.

9. The apparatus of claim 8, further comprising a beam expanding telescope to expand said polarized laser beam.

10. The apparatus of claim 9, further comprising a first polarizing beamsplitter oriented to transmit P-polarization and reflect S-polarization, wherein said polarized laser beam comprises P-polarization with respect to said first polarization beamsplitter, wherein said first polarizing beamsplitter transmits said polarized laser beam to produce beam 1.

11. The apparatus of claim 10, further comprising a second Faraday isolator configured to rotate the polarization of beam 1 counterclockwise 45° with respect to its direction of propagation, to produce beam 2.

12. The apparatus of claim 11, further comprising a first quartz rotator configured to rotate the polarization of said beam 2 clockwise 45° with respect to its direction of propagation, to produce beam 3.

13. The apparatus of claim 12, wherein said second Faraday isolator comprises a 45 mm diameter aperture.

14. The apparatus of claim 9, further comprising a 25 mm×25 mm square input mask.

15. The apparatus of 12, further comprising an anamorphic relay telescope, wherein said beam 3 comprises a

square 25 mm by 25 mm size, wherein said anamorphic telescope resizes said beam 3 to 8 mm×120 mm, wherein said apparatus further comprises a collimating lens to collimate said beam 3 after it is resized by said anamorphic relay telescope.

16. The apparatus of claim 15, wherein said means for providing 8 amplification passes of said polarized laser comprise:

- a second polarization beamsplitter configured to transmit beam 3, to produce beam 4;
- a plurality of optics defining a two pass optical cavity configured to receive said beam 4;
- an optical amplifier placed on the axis of said two pass optical cavity;
- a second quartz rotator configured to rotate the polarization of said beam 4 90° to produce beam 5;
- a third polarizing beamsplitter configured to reflect beam 5 onto said second polarizing beamsplitter such that beam 5 is collinear with beam 4, wherein said second quartz rotator is configured to rotate the polarization of beam 5 90°0 to produce beam 6, wherein said third polarizing beamsplitter is configured to transmit beam 6 to produce beam 7;
- a phase conjugator configured to receive and reverse the phase and direction of beam 7 to produce beam 8;
- wherein beam 8 propagates in reverse the beam path defined by beam 1 through beam 7 to produce a reverse beam.

17. The apparatus of claim 16, wherein said means for converting said at least one amplified beam into at least one output beam comprise said first quartz rotator, said first Faraday isolator and said first polarizing beamsplitter, wherein said first quartz rotator and said first Faraday isolator both rotate the polarization of said reverse beam 45° clockwise for a total rotation of 90°, wherein said first polarizing beamsplitter is configured to reflect said reverse beam to produce at least one output beam.

18. The apparatus of claim 1, wherein said at least one optical amplifier comprises a flashlamp-pumped Nd:glass zig-zag slab amplifier.

19. The apparatus of claim 1, wherein said at least one optical amplifier is selected to match the gain profile of said means for producing a polarized laser beam.

20. The apparatus of claim 1, wherein said means for producing a polarized laser beam comprise a free-running single frequency Nd:YLF master oscillator.

21. The apparatus of claim 1, wherein said means for reversing the phase of said polarized laser beam and its propagation direction comprise at least one phase conjugator composed of a closed cell filled with up to 100 atmospheres of compressed gas such as N_2.

22. The apparatus of claim 21, wherein each phase conjugator of said at least one phase conjugator comprises a unique pressure with respect to the other said phase conjugators of said at least one phase conjugator, wherein said output beam comprises multiple frequencies.

23. The apparatus of claim 16, wherein said providing means further comprises a 1:1 relay telescope optically oriented to transmit said beam 4, said 1:1 relay telescope located between said second polarizing beamsplitter and said optical amplifier.

24. The apparatus of claim 1, further comprising a second harmonic generator optically oriented to double the frequency of said output beam.

25. The apparatus of claim 1, wherein said optical amplifier comprises an 8 mm by 120 mm aperture.

26. The apparatus of claim **1**, wherein said providing means comprise:

4 mirrors to separate said polarized laser beam into four polarized laser beams;

4 Faraday isolators, each isolator of said 4 Faraday isolators optically positioned to transmit a different beam of said four polarized laser beams, wherein an optical amplifier of said at least one optical amplifier is optically positioned to transmit a different beam after it passes through an isolator of said 4 Faraday isolators;

wherein said phase reversing means comprise at least one phase conjugator optically aligned to reverse the phase and direction of said four polarized laser beams, said phase reversing means restoring a uniform output phase to all four said amplified output beams.

27. The apparatus of claim **26**, wherein said at least one phase conjugator comprises at least one four wave mixing stimulated-Brillouin-scattering phase conjugator.

28. The apparatus of claim **26**, wherein said reversing means comprise a different stimulated-Brillouin-scattering media in each phase conjugator of said at least one phase conjugator.

29. The apparatus of claim **26**, wherein said reversing means comprise a different pressure in each phase conjugator of said at least one phase conjugator.

30. The apparatus of claim **1**, further comprising a second harmonic generator optically positioned to double the frequency of said output beam.

31. An apparatus for producing a long-pulse, near diffraction limited quality optical output beam comprised of individual physical portions of said beam each operating at a separate, stable, narrow-bandwidth frequency but exactly co-linearly propagating, said apparatus comprising:

a laser master oscillator activated by a pulsed source and operated in a free running output mode to produce a polarized output laser beam pulse with an exponentially rising leading edge having a time constant τ determined from the formula:

$$\tau=1/(dG(t)/dt)-(P_{o}n/E_{sat}A);$$

at least one optical amplifier or a multiplicity thereof;

means for providing up to 8 amplification passes of said polarized output laser beam pulse with an exponentially rising leading edge, said amplification passes propagating through said optical amplifier to produce an output pulse with nearly constant output energy;

a separate phase conjugator for each portion of said individual physical portions, each said separate phase conjugator placed at the physical mid-point of said amplification passes and setup up in a 4 wave mixing stimulated Brillouin scattering (SBS) configuration to generate the reduced threshold required for long pulse operation and to simultaneously generate and maintain narrow bandwidth, high beam spatial quality and stable beam pointing by means of Stokes feedback in the SBS process of said SBS configuration;

means to direct said laser beam into and out of said optical amplifier by passively switching the polarization of said polarized output laser beam pulse and said output pulse with nearly constant output energy to cause them to appropriately reflect off or transmit through polarization dependent beam splitters.

32. An apparatus for producing a long-pulse-width narrow-bandwidth pulse, comprising:

means for producing an input laser beam comprising P-polarization with an exponentially rising leading edge having a time constant τ determined from the formula:

$$\tau=1/(dG(t)/dt)-(P_{o}n/E_{sat}A);$$

a first polarizing beamsplitter configured to transmit said input laser beam comprising P-polarization;

a first Faraday isolator configured to rotate the polarization of said input laser beam 45 degrees counter-clockwise with respect to its direction of propagation after passing through said first polarizing beamsplitter;

a first quartz rotator configured to rotate the polarization of said input laser beam 45 degrees clockwise with respect to its direction of propagation after passing through said first Faraday isolator;

a second polarizing beamsplitter configured to transmit said input laser beam after is passes through said first quartz rotator;

an optical amplifier;

a plurality of mirrors configured to provide two amplification passes through said optical amplifier;

wherein said plurality of mirrors provide two amplification passes of said input laser beam after it passes through said second polarizing beamsplitter;

a second quartz rotator configured to rotate the polarization of said input laser beam 90 degrees clockwise with respect to it's direction of propagation after a second pass of said input laser beam through said optical amplifier;

a third polarizing beamsplitter configured to reflect said input laser beam after it passes through said second quartz rotator, wherein said input laser beam is directed to reflect from said second polarizing beamsplitter, after said second pass of said input laser beam through said optical amplifier, to undergo two more passes through said optical amplifier, after which said second quartz rotator rotates the polarization of said input laser beam 90 degrees and said third polarizing beamsplitter transmits said input laser beam after it passes through said second quartz rotator;

a phase conjugator setup in a multipass, multi-focus geometry by means of a ring configuration of mirrors and reimaging optics and configured to receive said input laser beam after it passes through said third polarizing beamsplitter, wherein said input beam reverses its path, to produce an output direction laser beam, wherein said first quartz rotator is configured to rotate the polarization of said output direction laser beam 45 degrees clockwise with respect to its direction of propagation, wherein said first Faraday isolator is configured to rotate the polarization of said output direction laser beam 45 degrees clockwise with respect to its direction of propagation, wherein said first polarizing beamsplitter is configured to reflect said output direction laser beam to produce an output beam.

33. An apparatus for producing a long-pulse-width narrow-bandwidth pulse, comprising:

means for producing a polarized beam of light comprising P-polarization with an exponentially rising leading edge having a time constant τ determined from the formula:

$$\tau=1/(dG(t)/dt)-(P_{o}n/E_{sat}A);$$

a first polarizing beamsplitter configured to transmit said polarized beam of light to produce beam **1**;

a first Faraday isolator configured to rotate the polarization of beam 1 45° counter-clockwise to produce beam **2**;

a first quartz rotator configured to rotate the polarization of beam **2** 45° clockwise to produce beam **3**;

a second polarizing beamsplitter configured to transmit beam **3** to produce beam **4**;

a plurality of optics defining a two pass optical cavity configured to receive said beam **4**;

an optical amplifier placed on the axis of said two pass optical cavity;

a second quartz rotator configured to rotate the polarization of said beam **4** 90° to produce beam **5**;

a third polarizing beamsplitter configured to reflect beam **5** onto said second polarizing beamsplitter such that beam **5** is collinear with beam **4**, wherein said second quartz rotator is configured to rotate the polarization of beam **5** 90° to produce beam **6**, wherein said third polarizing beamsplitter is configured to transmit beam **6** to produce beam **7**;

a phase conjugator configured to receive and reverse the phase and direction of beam **7** to produce beam **8**;

wherein beam **8** propagates in reverse the beam path defined by beam **1** through beam **7** to produce a reverse beam, wherein said first quartz rotator and said first Faraday isolator both rotate the polarization of said reverse beam 45° clockwise for a total rotation of 90°, wherein said first polarizing beamsplitter is configured to reflect said reverse beam to produce an output beam.

34. A method for producing a long-pulse-width narrow-bandwidth output beam, comprising:

producing a polarized pulse with a laser master oscillator activated by a pulsed source and operated in a free running output mode, wherein said polarized pulse comprises an exponentially rising leading edge having a time constant τ determined from the formula:

$$\tau=1/(dG(t)/dt)-(P_o n/E_{sat}A);$$

passing said polarized pulse through at least one optical amplifier for a total of 8 amplification passes to produce at least one amplified beam with nearly constant output energy;

reversing, with a stimulated-Brillouin-scattering (SBS) configuration, the phase of said polarized pulse and its propagation direction after 4 passes through said at least one optical amplifier, wherein said amplified beam retraces its path and relative polarization through said at least one optical amplifier, thereby providing the reduced threshold required for long pulse operation while maintaining narrow bandwidth, high beam spatial quality and stable beam pointing by means of stokes feedback in the SBS process of said SBS configuration; and

converting said at least one amplified beam into at least one output beam by passively switching the polarization of said at least one amplified beam to cause it to appropriately reflect off or transmit through polarization dependent beamsplitters.

35. A method for producing a long-pulse-width narrow-bandwidth, near diffraction limited quality, optical output beam comprising:

producing a polarized output pulse with a laser master oscillator activated by a pulsed source and operated in a free running output mode, wherein said polarized output pulse comprises an exponentially rising leading edge having a time constant τ determined from the formula:

$$\tau=1/(dG(t)/dt)-(P_o n/E_{sat}A);$$

amplifying said polarized output pulse with up to 8 amplification passes through an optical amplifier to produce an output pulse with nearly constant output energy;

generating, with a phase conjugator placed at the physical mid-point of said amplification passes, the reduced threshold required for long pulse operation, wherein said phase conjugator is setup up in a 4 wave mixing stimulated Brillouin scattering (SBS) configuration while generating and maintaining narrow bandwidth, high beam spatial quality and stable beam pointing by means of Stokes feedback in the SBS process of said SBS configuration; and

directing said laser beam into and out of said optical amplifier by passively switching the polarization of said output pulse to cause it to appropriately reflect off or transmit through appropriate polarization dependent beamsplitters.

36. An apparatus, comprising:

means for producing a polarized low power laser beam with an exponentially rising leading edge having a time constant τ determined from the formula

$$\tau=1/(dG(t)/dt)-(P_o n/E_{sat}A);$$

at least one optical amplifier;

means for providing multiple amplification passes of said polarized low power laser beam, said multiple amplification passes propagating through said at least one optical amplifier to produce at least one amplified beam with nearly constant output power determined by said time constant of said exponentially rising leading edge of said polarized low power laser beam;

means for reversing the phase of said polarized low power laser beam and it propagation direction after half of said multiple amplification passes through said at least one optical amplifier, said reversing means including stimulated-Brillouin-scattering (SBS), wherein said amplified beam retraces its path and relative polarization through said at least one optical amplifier; and

means for converting said at least one amplified beam into at least one output beam by passively switching the polarization of said at least one amplified beam.

* * * * *

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United States Patent [19]

Hackel et al.

[11] Patent Number: 5,239,408

[45] Date of Patent: Aug. 24, 1993

[54] HIGH POWER, HIGH BEAM QUALITY REGENERATIVE AMPLIFIER

[75] Inventors: **Lloyd A. Hackel; Clifford B. Dane**, both of Livermore, Calif.

[73] Assignee: **Regents of the University of California**, Oakland, Calif.

[21] Appl. No.: **948,488**

[22] Filed: **Sep. 22, 1992**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 822,763, Jan. 21, 1992.

[51] **Int. Cl.**[5] **H01S 3/98**; H01S 3/093

[52] **U.S. Cl.** **359/338**; 359/348; 372/30; 372/94

[58] **Field of Search** 359/338, 346, 348; 372/20, 30, 94

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,191,928	3/1980	Emmett	372/94
4,725,787	2/1988	Chandra	359/348
4,943,782	7/1990	Stephens et al.	359/338
4,989,216	1/1991	Chandra et al.	372/97
5,022,033	6/1991	Hackell	372/94

OTHER PUBLICATIONS

Manes et al; Proceedings of the Laser Materials Processing; Nov,. 9, 1990 LIA, vol. 71, pp. 100–122; Abst. only provided.

(B) Ledneva et al; J. Appl. Spectrosc., vol. 36, #3, pp. 299–303, Mar. 1982, Abst only provided.

Dane et al; Proc. of SPIE, vol. 1626, pp. 297–307, Abst. only provided herewith.

Hachel et al.; DOE Conf. on Laser and Electro-Optic., May 25, 1990, 2 pages; Abst. only supplied.

Armandillo, E.; Regenerative Amplification In A XeCl Excimer Laser With A Phase-Conjugating Brillouin Mirror; Optics Communications, vol. 49, No. 3, Mar. 1, 1984, pp. 198–200.

Park et al.; Electronic Linewidth Narrowing Method For Single Axial Mode Operation Of Q-Switched Nd:YAG Lasers; Optics Communications, vol. 37,No. 6, Jun. 15, 1981, pp. 411–416.

Pashinin, et al.; Regenerative YAG:Nd^{3+} Amplifier With A Stimulated Brillouin Scattering Mirror; Sov. J. Quantum Electron., 18 (9), Sep. 1988, pp. 1092–1094.

Summers, et al.; Design and Performance Of A High Average Power Zigzag Slab Laser; Amosa (Optical Society of America); 1989 Annual Meeting, Technical Digest, Oct. 15–20 1989, p. 230.

Weaver, et al.; Multikilowatt Pockels Cell For High Average Power Laser Systems, J. Appl. Phys. 68 (6), Sep. 15, 1990 pp. 2589–2598.

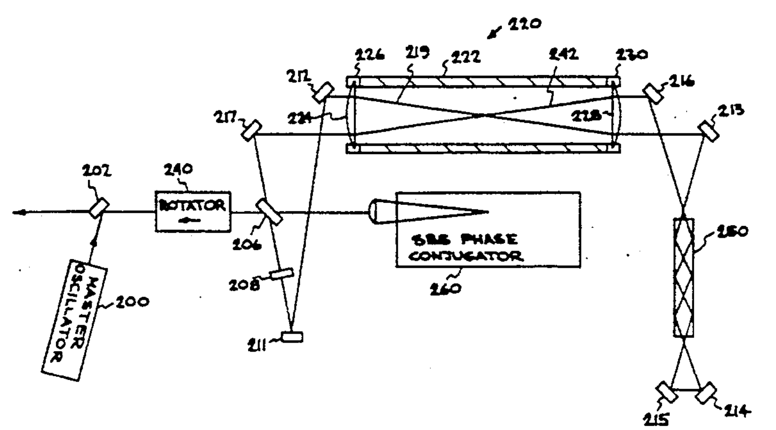
Yan, et al.; High-Repetition-Rate Nd:Phosphate Glass Regenerative Amplifier, Conference on Lasers and Electro-Optics, Apr. 26, to May 1, 1987, OSA/IEEE, Digest of Technical Papers, pp. 150–151.

Primary Examiner—Nelson Moskowitz
Attorney, Agent, or Firm—Henry P. Sartorio

[57] **ABSTRACT**

A regenerative laser amplifier system generates high peak power and high energy per pulse output beams enabling generation of X-rays used in X-ray lithography for manufacturing integrated circuits. The laser amplifier includes a ring shaped optical path with a limited number of components including a polarizer, a passive 90 degree phase rotator, a plurality of mirrors, a relay telescope, and a gain medium, the components being placed close to the image plane of the relay telescope to reduce diffraction or phase perturbations in order to limit high peak intensity spiking. In the ring, the beam makes two passes through the gain medium for each transit of the optical path to increase the amplifier gain to loss ratio. A beam input into the ring makes two passes around the ring, is diverted into an SBS phase conjugator and proceeds out of the SBS phase conjugator back through the ring in an equal but opposite direction for two passes, further reducing phase perturbations. A master oscillator inputs the beam through an isolation cell (Faraday or Pockels) which transmits the beam into the ring without polarization rotation. The isolation cell rotates polarization only in beams proceeding out of the ring to direct the beams out of the amplifier. The diffraction limited quality of the input beam is preserved in the amplifier so that a high power output beam having nearly the same diffraction limited quality is produced.

26 Claims, 4 Drawing Sheets



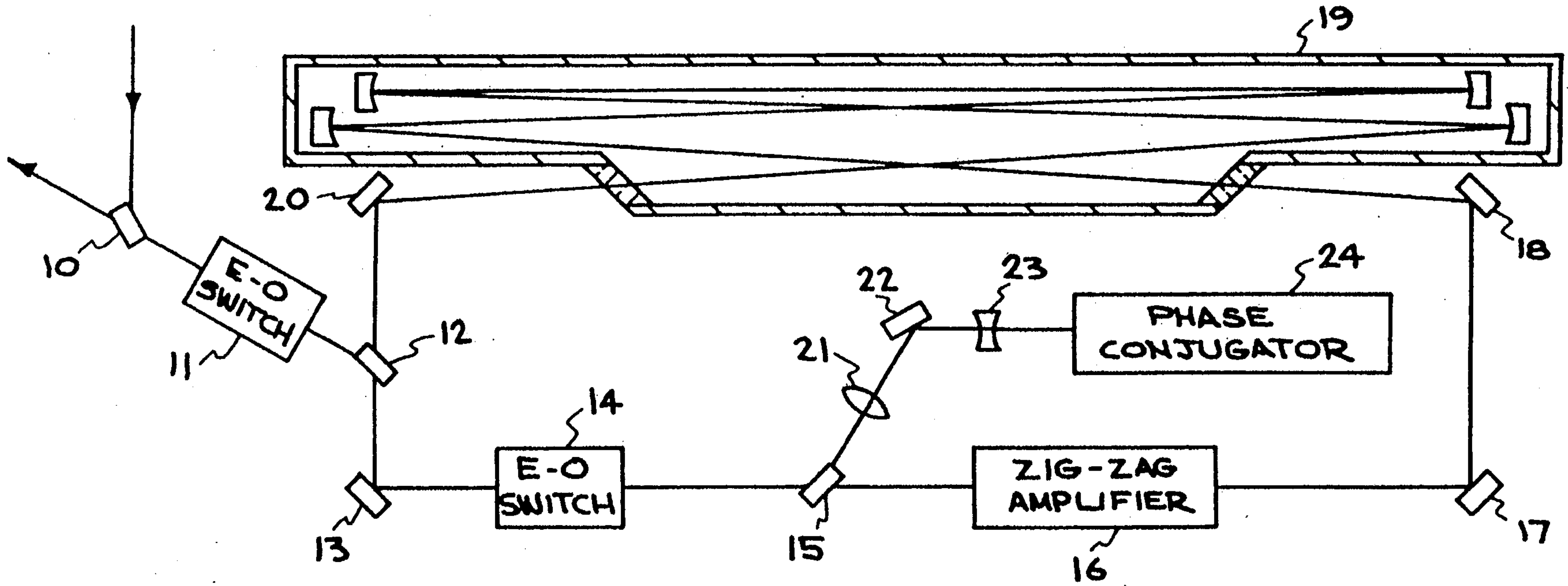
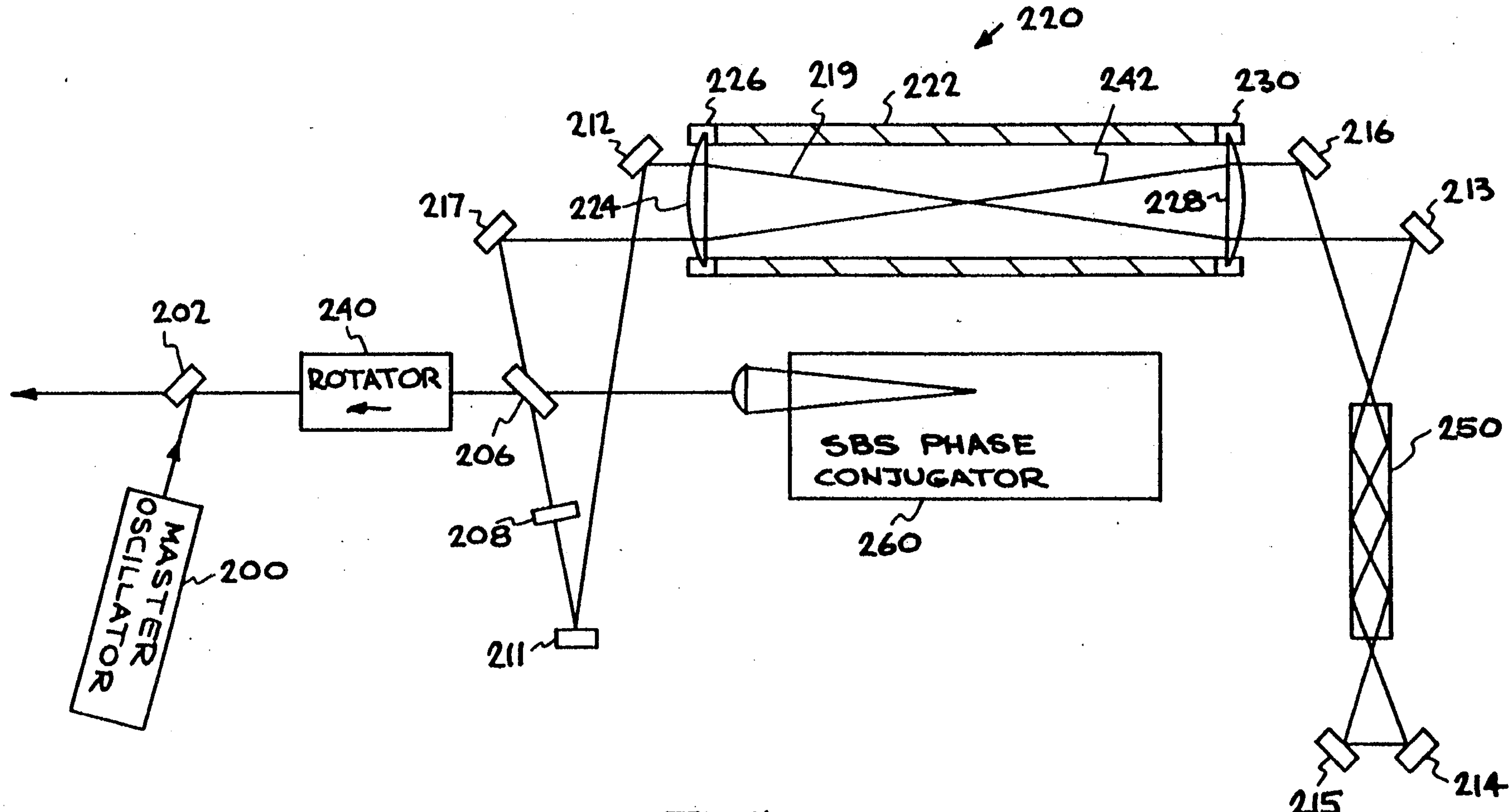


FIG. 1
(PRIOR ART)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MASTER OSCILLATOR
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FIG. 2

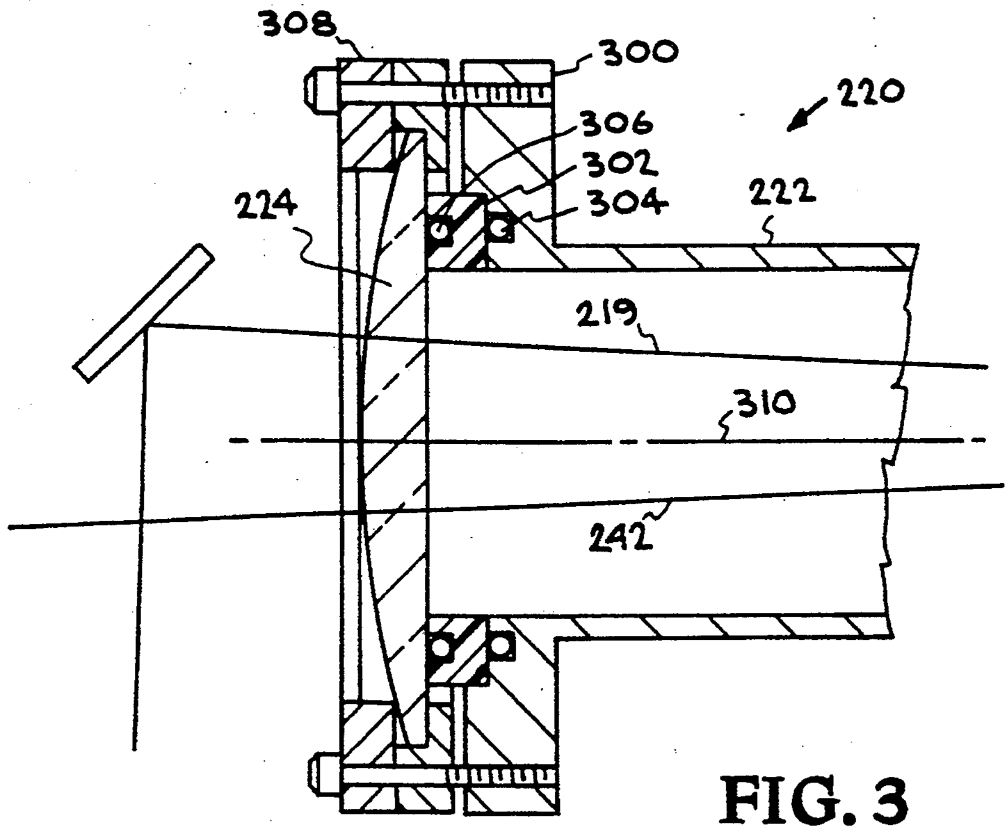
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FIG. 3

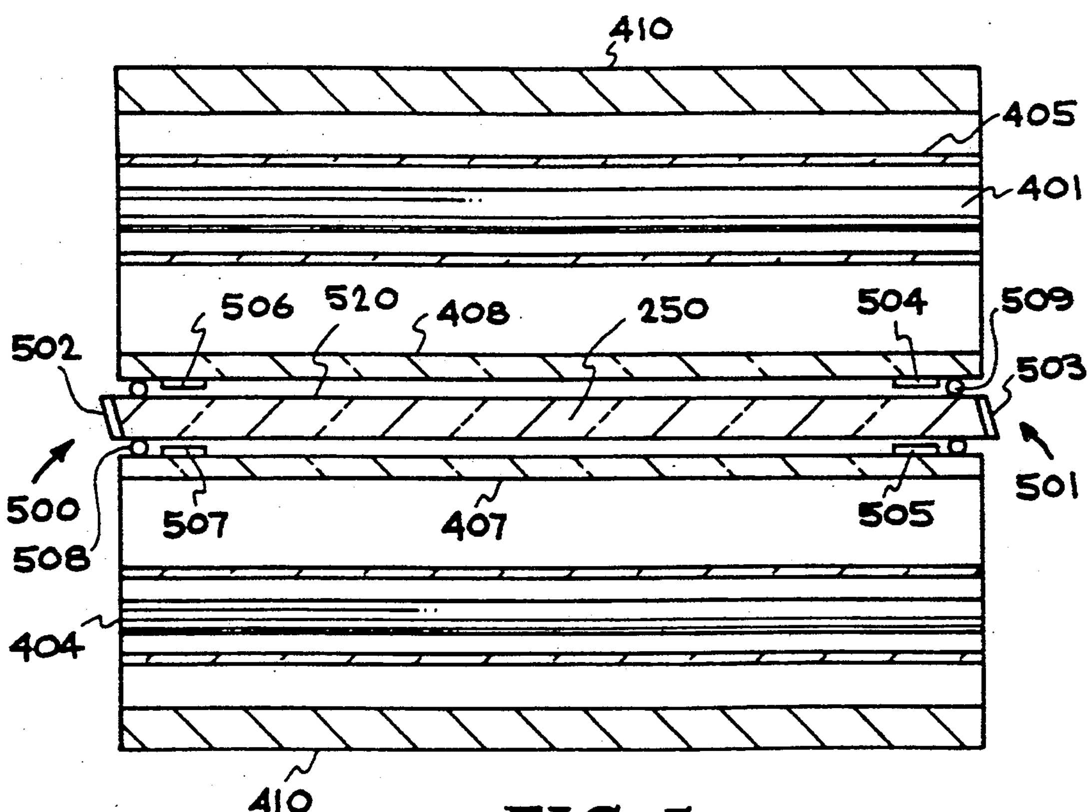
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FIG. 5

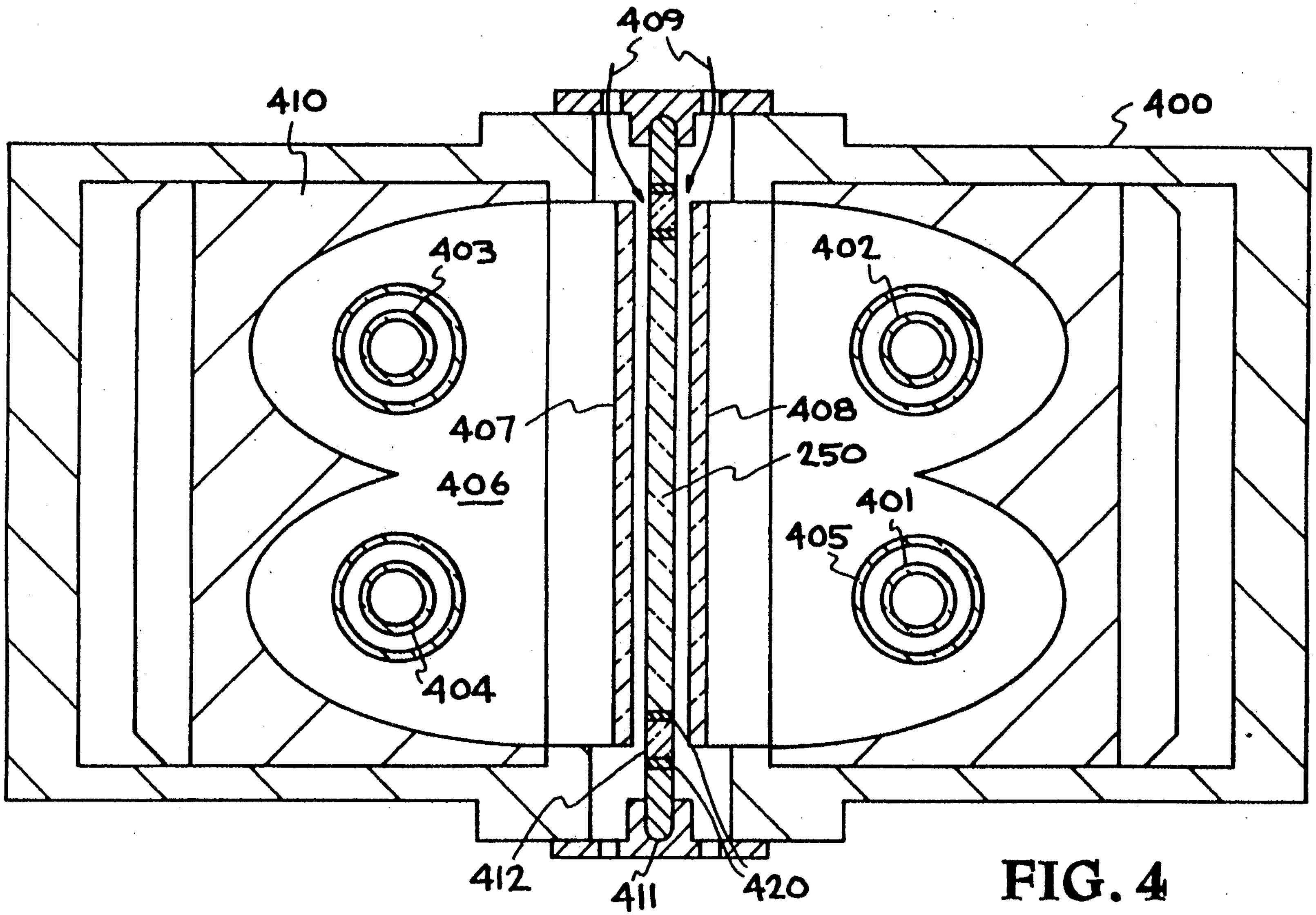

FIG. 4

HIGH POWER, HIGH BEAM QUALITY REGENERATIVE AMPLIFIER

The United States government has rights in this invention pursuant to Contract Number W-7405-ENG-48 between the United States Department of Energy and the University of California for the operation of Lawrence Livermore National Laboratory.

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of U.S. patent application entitled HIGH POWER REGENERATIVE LASER AMPLIFIER, Ser. No. 07/822,763, filed Jan. 21, 1992, invented by Hackel, et al., which is incorporated herein by reference. Applicant claims priority from said application pursuant to 37 C.F.R. §1.78.

BACKGROUND

1. Field of the Invention

The present invention relates to laser amplifiers, and particularly to laser amplifiers generating high peak power and high energy per pulse output beams, e.g., for generating X-rays used in the process of X-ray lithography for manufacturing of integrated circuits.

2. Description of Related Art

High power laser amplifiers have a wide variety of applications. One important example is in the generation of X-rays used for X-ray lithography in the manufacture of integrated circuits. To generate X-rays, 1–20 nanosecond pulses of infrared radiation of about 20 joules per pulse with peak powers over a gigawatt are needed. Also, these pulses must be generated from five to ten times per second to achieve sufficient performance for cost effective production of integrated circuits. These high power infrared pulses are directed onto a tape impregnated with an iron oxide, which generates an X-ray in response to the stimulation of the infrared pulse. The X-rays are then used to illuminate resist coated wafers in the X-ray lithography process producing integrated circuits.

The design of laser amplifiers which can achieve these performance goals has been limited in the prior art by a variety of factors related to the tolerance of optical components in the amplifier to pulses of high energy laser light.

For instance, in one large class of amplifier designs, known as regenerative amplifiers, multiple passes through a single gain medium, or plural gain media, are used for efficient extraction of energy. In these regenerative amplifiers, an optical path is defined around which an input pulse transits a number of times.

The efficient extraction of energy from the gain medium is limited, however, by losses in optical components in the path, such as electro-optic switches, polarizers, and the like. For amplifiers which involve numerous transits of the optical path, a small loss in a single component can decrease the gain to loss ratio of the amplifier significantly.

Furthermore, the optical components typically have peak power damage thresholds. Perturbations or diffraction in the beam as the beam transits the optical path can cause the beam to exceed these peak power damage thresholds. This results in damage to the optics and loss in efficiency in the regenerative amplifier.

Another limitation in these multipass systems resides in average power thresholds of optical components in the optical path. For systems which involve a number of transits of the optical path and repetitive pulsed operation, the average power dissipated in a given optical element can be quite high.

A representative regenerative amplifier design of the prior art is shown in FIG. 1, which is a schematic diagram of a high average power amplifier described by Summers, et al., "Design Performance of a High Average Power Zig-Zag Slab Laser", Optical Society of America, 1989 Annual Meeting in Orlando, Fla.

The amplifier design of FIG. 1 includes a first polarizer 10, a first electro-optic switch or Pockels cell 11, a second polarizer 12, a first mirror 13, a second Pockels cell 14, a third polarizer 15, a zig-zag amplifier 16, a second mirror 17, a third mirror 18, an anamorphic vacuum relay (telescope) 19, and a fourth mirror 20. Also, a lense 21, fifth mirror 22, lense 23, and phase conjugator 24 are included in the amplifier system.

In operation, an input pulse is supplied incident on the first polarizer 10, and having a polarization which is reflected by the polarizer 10. This input beam passes through the first Pockels cell 11 without rotation, and is reflected by the second polarizer 12 into a ring shaped optical path. From the second polarizer 12, the pulse proceeds to mirror 13 and Pockels cell 14, where it is rotated to a polarization which is transmitted by the third polarizer 15. It then proceeds through the zig-zag amplifier 16, mirror 17, mirror 18, telescope 19, mirror 20, through second polarizer 12, to mirror 13, and through the Pockels cell 14 without rotation. Thus, the pulse is captured within the ring for a number of passes to achieve high gain. After one or more passes through the amplifier 16, the Pockels cell 14 causes the pulse to rotate so that it is reflected by third polarizer 15 into the phase conjugation leg of the amplifier. When it returns from the phase conjugator 24, it is again reflected by third polarizer 15 and supplied through Pockels cell 14 where it is rotated back to the polarization transmitted by the polarizers. It is then captured within the ring proceeding in the opposite direction for one or more passes through the amplifier. To couple the pulse out of the ring, the Pockels cell 14 rotates the pulse proceeding from third polarizer 15 toward mirror 13 so that it is reflected by second polarizer 12 through Pockels cell 11. Pockels cell 11 rotates the pulse so that it is transmitted by first polarizer 10 and supplied as an output beam.

This amplifier design demonstrates many of the limitations of the prior art. As can be seen, each pass through the amplifier 16 in which gain is achieved also involves a pass through a number of elements which can cause significant loss, including the telescope 19, the polarizers 12 and 15, and the electro-optic switch, implemented by the second Pockels cell 14.

Also, each of these elements is sensitive to perturbations in the beam. To limit the damage caused by perturbations, the relay telescope 19 relays an image near the amplifier 16 back onto itself. However, mirrors of the relay telescope 19 are far from the image plane, and thus diffraction of the beam in propagating from the plane results in intensity spiking and limited power.

Because of the above listed limitations, the amplifier design of FIG. 1 is impractical to use for producing the energy per pulse and peak power required in production of integrated circuits using X-rays, and for a variety of other applications. Accordingly, it is desirable to provide an amplifier design overcoming these prior art limitations.

SUMMARY OF THE INVENTION

Thus, it is desirable to reduce the amount of diffraction or phase perturbations in the output of the amplifier system to limit high peak intensity spiking. It is also desirable to provide an amplifier system capable of operating to enable efficient generation of X-rays for X-ray lithography.

The present invention provides an amplifier system which includes a ring shaped optical path with a limited number of components. The optical path includes an internal polarizer, a passive 90 degree phase rotator, a plurality of mirrors, a relay telescope, and a slab shaped gain medium. For inputting and outputting a pulse, the amplifier further includes a master oscillator, an external polarizer, and a one-way isolation rotator. The amplifier further includes a phase conjugator to enable reduction of phase aberrations.

In operation, a signal is input into the system at the external polarizer by a master oscillator which generates a beam with a polarization causing the beam to reflect off of the external polarizer. The beam will then proceed from the external polarizer through the isolation rotator, with no polarization change to enter the ring through the internal polarizer.

The pulse input into the ring shaped optical path is reflected by the internal polarizer and proceeds through a passive 90 degree phase rotator where polarization is rotated. The pulse then proceeds from the 90 degree phase rotator through first and second mirrors to a relay telescope. From the telescope, the beam proceeds through a third mirror into a gain medium, or slab where it is reflected by fourth and fifth mirrors back through the slab. From the slab, the beam is reflected off a sixth mirror back through the telescope and off a seventh mirror where it is reflected into the internal polarizer, thus completing one path around the ring.

The beam now having a polarization to pass through the internal polarizer will proceed for a second pass through the ring as described above. In the second pass, polarization rotation by the 90 degree rotator causes the beam to reflect off the internal polarizer into a stimulated Brillouin scattering (SBS) phase conjugator. The beam proceeding back out of the phase conjugator will also be reflected by the internal polarizer to proceed around the ring twice in the opposite direction.

After two passes around the ring in the opposite direction, polarization rotation by the 90 degree rotator causes the beam to reflect off of the internal polarizer out of the ring into the isolation rotator, e.g., Pockels cell. The isolation rotator rotates the polarization of the outgoing beam so that the beam will be output by the external polarizer.

The components of the present invention and their configuration as described above achieve reduced intensity spiking from diffraction and phase perturbations by first utilizing two paths around a ring shaped optical path before entering the SBS phase conjugator and two equal paths around the ring in the opposite direction but with reversed phase after exiting the SBS phase conjugator. The phase reversal and subsequent propagation through the amplifier results in essentially zero net phase aberration in the output beam.

Further, the Pockets cell is removed from the ring and replaced by a passive phase shifter so that no switching in the ring is required. A typical Pockels cell has approximately fourteen surfaces and will create more diffraction or phase perturbations than a two surface passive phase shifter. Also, with a passive phase shifter in the ring, the length of an input pulse may be as long as four times the distance of one transit of the ring. Also, with a passive phase shifter in the ring and a Faraday rotator replacing the input/output Pockels cell, no active switching is required and any length pulse can be amplified.

Another advantage of the amplifier configuration of the present invention is the placement of components near the telescope which involves, in effect, two relay telescopes. Use of the telescope of the present invention reduces diffraction caused by the significant distances between mirrors in the telescope of FIG. 1. Also, there are at least two passes through the slab for each transit of the optical path improving the gain to loss ratio of the ring.

Because of the combination of passive rotator and reflection (here by the phase conjugator) no Pockels cell switch is needed inside the ring. The configuration of components in the system allows the Pockets cell outside the ring to be an isolation Pockels cell which changes the beam phase as the beam passes through the Pockels cell in the direction only. Also, a passive Faraday rotator can be used.

BRIEF DESCRIPTION OF THE DRAWINGS

Further details of the present invention are explained with the help of the attached drawings in which:

FIG. 1 is a schematic diagram of a prior art regenerative laser amplifier system;

FIG. 2 is a schematic diagram of the regenerative laser amplifier according to the present invention;

FIG. 3 is an expanded view of a lense mounted in the laser amplifier system shown in FIG. 2;

FIG. 4 is a schematic cross-section orthogonal to the optical path of the slab FIG. 2 and its enclosing pump cavity; and

FIG. 5 is a schematic cross-section of the slab of FIG. 2 and enclosing pump cavity taken parallel to the optical path.

DETAILED DESCRIPTION

FIG. 2 is a schematic diagram of the regenerative laser amplifier according to the present invention. The amplifier of FIG. 2, includes a master oscillator **200**, a rotator **240**, such as a Pockels cell or Faraday rotator, a relay telescope **220**, a slab-shaped gain medium **250**, and an SBS phase conjugator **260**. The slab **250** is enclosed in a pump cavity (not shown). Two polarizers **202** and **206** are also included for capturing an input pulse, and extracting an output pulse. Seven flat, highly reflecting mirrors **211**, **212**, **213**, **214**, **215**, **216**, and **217**, define an optical path through the slab **250**, and telescope **220**, and polarizer **206** connects the ring to SBS phase conjugator **260**.

In operation, a master oscillator **200** supplies an input pulse which has S polarization. The pulse reflects off polarizer **202**, proceeds through an isolation Pockels cell **240** remaining unchanged in polarization, and is further reflected off polarizer **206** into a ring shaped optical path defined by mirrors **211–217**.

In the ring, the beam enters the 90 degree rotator **208** which rotates the beam by 90° to the P polarization. The pulse proceeds through mirrors **211** and **212** along optical path **219** through relay telescope **220**.

The telescope 220 includes a vacuum chamber 222 having a first lens 224 mounted by a vacuum tight seal 226, and a second lense 228 mounted by vacuum tight seal 230. In an illustrative embodiment, each of the lenses 224 and 228 is a 1.2 meter focal length lense. The spacing between lenses 224 and 228 is approximately 2.4 meters adjusted so that the lense pair is afocal.

From telescope 220, the beam proceeds through mirror 213 into and through the slab 250 where it is reflected by mirrors 214 and 215 back through the slab 250. Near unity fill of the pumped volume is accomplished by a first zig-zag pass and a second zig-zag pass which are essentially mirror images about the direction of propagation. In this way, the second zig-zag pass will tend to extract gain from regions that may have been missed in the first pass.

From slab 250, the beam is reflected off mirror 216 along path 242 through telescope 220, off mirror 217 where it is reflected back into polarizer 206. Since the beam has been rotated by the 90 degree rotator 206 from the S polarization to the P polarization, the P polarized beam is transmitted by polarizer 206 to 90 degree rotator 208 to proceed through the ring a second time. However, during this second pass through the ring, 90 degree rotator rotates the polarization by 90° back to the S polarization. Therefore, when the beam reaches the polarizer 206 at the end of a second pass through the ring, it will be reflected into SBS phase conjugator 260.

The beam proceeding back out of the SBS phase conjugator, still having the S polarization, but reversed phase error will be reflected by polarizer 206 to mirror 217 where it will proceed along path 242 through telescope 220 to mirror 216. From mirror 216. From mirror 216, the beam will proceed through slab 250 a first time and be reflected back through the slab 250 a second time by mirrors 214 and 215. Proceeding out of slab 250, the beam will be reflected off mirror 213 and proceed back through telescope 220 and mirrors 212 and 211 to 90 degree rotator 208. The 90 degree rotator 208 will rotate the polarization by 90° back to the P polarization and transmit the beam to polarizer 206, thus completing a third pass through the ring, but this time in the reverse direction from the first two passes.

Since the beam has a P polarization, the beam will pass through polarizer 206 and proceed through the ring for a fourth pass through the ring, or a second pass in the reverse direction. At the end of this fourth pass through the ring, 90 degree rotator will rotate the polarization back to the S polarization causing the beam to reflect off of polarizer 206 out of the ring and into isolation Pockels cell 240. By this point, the net accumulated phase error is essentially zero. Isolation Pockels cell 240 or Faraday rotator will rotate the polarization of the beam to the P polarization enabling the beam to pass through polarizer 202 as a high energy output pulse.

Thus, the amplifier illustrated in FIG. 2 exhibits reduced diffraction, minimizing the likelihood of high peak perturbations in a beam, by utilizing two paths around the ring before entering the phase conjugator, and two equal and opposite paths around a ring after exiting the phase conjugator. The ring, further, utilizes a passive phase shifter instead of a Pockels cell. Additionally, all optical components are placed near the image planes by the use of two relay telescopes. The amplifier also exhibits higher gain to loss, with two slab passes per ring transit.

Each of the components of the amplifier of the present invention are described as follows.

Master Oscillator 200

The single frequency master oscillator 200 in FIG. 2 is implemented with a self seeding, Nd:YLF flash lamp pumped laser, derived from a self-seeded laser concept for Nd:YLF described in U.S. Pat. No. 4,022,033, issued Jun. 4, 1991, by Lloyd Hackel. It generates an output pulse of approximately 50 millijoules at 10–50 hertz, in a single spatial mode TEM_{00} and a single temporal mode at a wavelength near 1.053 micrometers. The output pulse beam of the master oscillator 200 has a diameter of approximately 3 mm.

Alternative oscillators which provide a pulse or series of pulses of high power laser radiation at consistent single frequency with good amplitude and temporal stability can be used.

Rotator Cell 240

The rotator 240 in one embodiment is implemented using a Pockels cell capable of handling up to one kilowatt average power in an aperture of 12 mm×140 mm. The electroactive material is potassium dihydrogen phosphate (KDP) with its deuterated isomorph, KD*P (greater than 93% deuterated). The deuterated isomorph is used to lower the optical absorption and obtain higher electro-optic coefficients. This Pockels cell is thermally compensated and designed according to the parameters described in Weaver, et al., "Multi Kilo-Watt Pockels Cell for High Average Power Laser Systems", J. Appl. Phys., 68 (6), Sep. 15, 1990, pp. 2589–2598. It is a 90° polarization rotator with no applied voltage. Other Pockels cell designs capable of meeting the average and peak power standards of the amplifier may be used. Also, the Pockels cell should have low loss, i.e., greater than 95% transmission. Further, a large aperture is required to sustain the large rectangular beam amplified by the slab 250. The damage threshold of greater than 4 joules per cm^2 for the pulse lengths generated is required. These parameters are met using KD*P plates manufactured by Cleveland Crystals, Inc., in Cleveland, Ohio.

In an alternative embodiment, the rotator 240 is implemented with a Faraday rotator, which requires no active switching. The Faraday rotator is configured for no rotation of a beam going in the input direction, and 90° rotation of a beam going in the output direction.

Polarizers 202 and 206

The polarizers 202 and 206 in FIG. 2 are thin film polarizers composed of high damage threshold material such as hafnia/silica in multiple layers, on a fused silica substrate. Such polarizers are commercially available from OCLI in Santa Rosa, Calif.

The coated faces of the polarizers 202 and 206 face the Pockels cell 240. The polarizers are mounted at Brewster's angle.

Polarizers 202 and 206 provide both an input coupling and an output coupling function. Alternative designs may use separate components for these functions.

Mirrors 211–217

All seven mirrors in the optical path of the embodiment of FIG. 2 are formed by flat, highly reflecting, high damage threshold mirrors manufactured with hafnia/silica coatings, with reflectivity near 99.9% at the wavelength of the amplifier.

Telescope 220

FIG. 3 is an expanded view of the end of the telescope 220 containing lense 224 as shown in FIG. 2. As can be seen, the telescope vacuum chamber 222 includes a flange 300. A lense mount spacer 302 (made of acetal thermoplastic, known in the trade as Delrin, or other suitable materials) is placed on flange 300 and sealed by O-ring 304. Lense 224 is placed adjacent to lense mount spacer 302 and sealed by O-ring 306. The lense 224 is mounted in a lense holder 308 exposing the outside surface of the lense to the beam.

In order to allow adjustment, the lense mount spacer 302 can be machined by mechanical shaving after experimental measurement of the focal lengths at low power. Using this technique, the lense pair is adjusted so that they are afocal.

Commercially available 25 cm high BK7 lenses are used, with 1.2 meter focal lengths. As can be seen, beams 219 and 242 proceed off axis 310 of the lenses. Using the 25 cm high lenses, a 1 cm wide$\times$10 cm high beam, slightly off axis, is transmitted with minimum distortion. Other size lenses could be used as suits the needs of a particular application. Also, materials such as fused silica may be used for the lense in order to improve the damage threshold, if necessary.

The vacuum chamber 222 is evacuated to approximately 10^{-4} torr, to prevent air breakdown at the focal point of the optical relays.

Slab 250

FIGS. 4 and 5 illustrates the slab 250 of FIG. 2 which is enclosed in a pump cavity. FIG. 4 is a schematic cross-section taken transverse to an optical path through slab 250, while FIG. 5 is a schematic cross-section taken parallel to the optical path.

As can be seen in FIG. 4, the slab 250 is mounted within a pump cavity 400 with 4 lamps 401, 402, 403, and 404. Lamps 401, 402, 403 404 are Xenon flash lamps mounted within respective coolant jackets (e.g., 405) as known in the art. These lamps are in turn mounted in a flooded reflector cavity 406. Plates of glass 407, 408 are mounted on each side of the slab 250 to establish a channel for the flow of cooling water in contact with the slab 250 as indicated at arrows 409. The flooded reflector cavity is encased by a diffuse reflector 410, such as a Spectralon (trademark) coated reflector which is commercially available from Labsphere, Inc. in North Sutton, N.H.

The slab 250 is secured to mounting bar 411 on each side. Between the mounting bar 411 is an absorbing glass plate 412 which absorbs the radiation subject to gain within the slab 250 to prevent parasitic oscillation transverse to the preferred optical path. Between the absorbing glass plate 412 and the slab 250, an index matching material 420 called Urapol 35-79X (manufactured by Dow Chemical Co., Sarnia, Ontario, Canada and available within the United States) is used to bond the slab 250 to the plate 412 and mounting bar 411. The Urapol serves to insulate the slab from heat absorbed in the glass 412, and prevent reflections at the interface between the slab and the mount.

Between the glass plates 407, 408 and the slab 250, a 1 mm gap is provided to allow flow of cooling water along path 409 on each side of the slab. Positive and negative pressure pumps on either side of the slab are used to maintain the water pressure on the slab at near atmospheric pressure, while establishing a turbulent flow of cooling water.

In the preferred system, the slab is a 10 mm$\times$140 mm$\times$419 mm slab of neodymium doped glass, doped in the range of 3 to $3.5\times10^{20}/cm^3$. Suitable glass materials include APG1 glass manufactured by Schott Glass in Duryea, Penn., or HAP4 from Hoya Optics in Fremont, Calif.

FIG. 5 is a schematic cross-section taken parallel to the optical path through the slab 250 of FIG. 2 which is enclosed in a pump cavity. It illustrates first that the input face 500 and the output face 501 of the slab are slightly wedged at 88.5° with respect to top surface 520 of slab 250 and parallel, to prevent parasitic oscillation within the slab. Additionally, the faces 500, 501 include anti-reflective coatings 502, 503, preferably manufactured of high tolerance multi-layer hafnia/silica, or other suitable materials such as Solgel available at Lawrence Livermore National Laboratory. Thus, the slab faces 500, 501 allow low loss transmission essentially independent of polarization. In particular, the slab can receive the pulse in either the P or S polarization as it transits around the optical path.

In addition, FIG. 5 illustrates a technique used to minimize perturbations generated in the slab. Because of the zig-zag optical path in the slab, there is a potential that different portions of the beam entering one face 500 may see different optical paths as they propagate through the slab. In order to ensure that the gain profile of all points along the beam are relatively uniform, shades formed by shims 504, 505, 506, 507 are mounted near the faces 500, 501 of the slab. These shims 504, 505, 506, 507 are used to tailor the length of the pump cavity relative to the slab, and ensure that the input and output shadows match. An alternative way of accomplishing this goal is to shorten the reflector flash lamp assembly so that the ends of the slab near faces 500, 501 are not illuminated. Shim widths are determined using computer modelling of the pump energy profile and optical paths within the slab. For a 10 mm thick slab having faces with 43° wedges, a tip to tip optical path length of 418.7 mm and a total of 10 internal reflections so that the incident angle at the entrance face is 56.74°, the pumped length of the slab is 326.6 mm.

Also, FIG. 5 illustrates the use of O-rings 508, 509 as water seals to enclose the cooling fluid between the slab and the glass plates 407, 408. Because of the positive and negative pressure pumps used to supply the cooling fluid, light O-ring pressure is sufficient to seal the pump cavity.

The glass in the flashlamp envelopes 401, and tubes, e.g., 405, are cerium doped glass to absorb ultraviolet radiation from the flashlamps and prevent solarization of the components in the pump cavity. Also, it may be desirable to dope the glass in the windows 407, 408 to absorb light with a wavelength shorter than about 400 nm.

The reflector illustrated in FIG. 4 is shaped according to a computer modelling based on the height of the slab, the number of flashlamps, the diameter of the plasma within the flashlamps, and the doping in the slab. This computer modelling generates an x-y position for the flashlamps and a shape for the reflector to achieve a substantially uniform pumping energy within the slab.

According to the computer modelling, the reflector contour is defined as follows.

Define the reflector contour f(x) based on the cubic:

$a=9$

$b=-0.5$

$c=0.5$

$d=-0.234375$

Original equation: $fo(x)=a+bx+cx^2+dx^3$
Symmetry axes at $+-s$: $s=3.2$
Half-aperture: $xmax=7.2$

Composite reflector curve:
$x < -s$: $f(x) = fo(-x-s)$
$-s < x < o$: $f(x) = fo(x+s)$
$o < x < s$: $f(x) = fo(-x+s)$
$s < x$: $f(x) = fo(x-s)$

The lamp locations (at y=5.65 cm, and x=+/−3.8 cm) were arrived at by iterating variables to maximize source flatness at the slab plane.

This gain medium configuration having pulsed flash lamps establishes an effective gain lifetime within the slab on the order of a few hundred microseconds.

Using the passive Faraday rotator as the external isolation rotator, the input pulse may have a length on the order of the effective gain lifetime of a slab. In effect, the passive switching of the input beam into the optical path of the amplifier and out of the optical path of the amplifier allows a pulse of any desired length. This pulse length is only limited by the gain characteristics of the gain medium, pump source combination.

SBS Phase Conjugator 260

Design parameters for a stimulated Brillouin scattering (SBS) phase conjugator can be found in a variety of texts available to those skilled in the art. The conjugator can be made of a 20 cm long glass cell with quartz window. A 10 cm focal length lens is used to focus the input light in CCl_4 liquid filling the cell. Prior to use, the liquid is filtered through a fine 1 micrometer sized filter system. Many other liquids or gases can be used.

Conclusion

For applications such as X-ray lithography discussed above, 20 joules per pulse with a 5-7 nanosecond pulse at 3-10 hertz is required. This will result in the generation of $10 mJ/cm^2$ per pulse of X-rays at a target at a standoff of 20 cm, when used with iron oxide tape as the point source. The amplifier configuration of the present invention is well suited for such applications.

The present invention is capable of producing such high energies in part because it minimizes the number of lossy optical elements in the path of the high energy pulses, takes steps to reduce diffraction, takes steps to increase the gain to loss ratio of the amplifier and takes steps to minimize phase aberrations.

The components of the present invention as shown in FIG. 2 and as described above achieve reduced diffraction or phase perturbations by first utilizing two paths around the ring before entering the SBS phase conjugator 260 and two equal paths now with reversed phase around the ring in the opposite direction after exiting the SBS phase conjugator 260. The aberrations incurred in the first two amplifier passes are essentially identical to those incurred in the last two passes. However, since the conjugator reverses the phase of the first two passes, the accumulated phase error upon exit is zero.

Further, no active switching in the ring is required. Thus, the pulse length is limited only by the input and output coupling. Using a Pockels cell as the input isolation rotator, the effective pulse length is limited by four times the ring length less the distance travelled during the time the Pockels cell switches. With the passive isolation rotator, such as one based on the Faraday rotator, an input pulse of any desired length may be used. Thus, the amplifier configuration of the present invention allows high power, high beam quality, and long pulse lengths in a combination not achieved in the prior art.

Another advantage is the placement of components near the telescope 220 which involves, in effect, two relay telescopes, one to relay a pulse to the slab 250 and one to relay a pulse from the slab 250. Using the telescope 220 reduces diffraction caused by the significant distances between mirrors in the telescope of FIG. 1.

Additionally, a beam path is utilized enabling at least two passes through the slab 250 for each transit of the optical path improving the gain to loss ratio of the ring. Furthermore, the slab 250 includes first and second faces transverse to the optical path which permit transmission of light substantially independent of the polarization. This configuration allows for near unity fill of the slab, and thus, efficient extraction.

In the amplifier system of the present invention an input beam having a diffraction limited quality generates an amplified signal having nearly the same diffraction limited quality. Measured results show substantially no degradation of diffraction limited quality through the amplifier.

Although the invention has been described above with particularity, this was merely to teach one of ordinary skill in the art how to make and use the invention. Many modifications will fall within the scope of the invention, as that scope is defined by the following claims.

What is claimed is:

1. A laser amplifier, comprising:
a gain medium;
a polarization rotator;
a passive polarizer;
a plurality of reflectors configured to define an optical path through the gain medium, the passive polarizer, and the polarization rotator; and
a phase conjugator configured to receive a beam from the optical path after the pulse has proceeded one or more transits through the optical path, the phase conjugator further configured to return the beam with reversed phase to the optical path to proceed an equal number of transits of the optical path in an opposite direction before exiting the optical path;
wherein a transit of the beam through the optical path includes a plurality of passes through the gain medium and only one pass through the polarization rotator and the passive polarizer.

2. The laser amplifier of claim 1, wherein the plurality of passes through the gain medium compsises two zigzag passes which in combination accomplish near unity fill of the gain medium.

3. The laser amplifier of claim 1 wherein the polarization rotator rotates the pulse by 90 degrees during each transit through the optical path.

4. The laser amplifier of claim 1 wherein the phase conjugator is a stimulated Brillouin scattering phase conjugator.

5. The laser amplifier of claim 1 further comprising:

means for generating the beam with a first polarization;

an external polarizer reflecting the beam from the generating means with the first polarization, but transmitting a beam with a second polarization; and

an external polarization rotator which receives the beam reflected from the external polarizer and transmits the pulse with no polarization change into the optical path, and which receives the beam exiting the optical path and rotates the beam to the second polarization so that the beam will proceed through the external polarizer as an amplified output pulse.

6. The laser amplifier of claim 5 wherein the external polarization rotator includes an isolation Pockels cell.

7. The laser amplifier of claim 5 wherein the external polarization rotator includes an isolation Faraday rotator.

8. The laser amplifier of claim 1 further comprising a source of pump energy coupled with the gain medium.

9. The laser amplifier of claim 8, wherein the gain medium comprises a slab, and the source of pump energy comprises a pump cavity, enclosing the slab, and supplying a substantially uniform pump energy distribution in the slab to minimize perturbations in the beam.

10. The laser amplifier of claim 8, wherein the gain medium comprises a slab consisting of Nd:glass, and the source of pump energy comprises a pump cavity, enclosing the slab, and supplying a substantially uniform pump energy distribution in the slab to minimize perturbations in the beam.

11. The laser amplifier of claim 1, wherein the gain medium includes first and second faces transverse to the optical path, and wherein the first and the second faces permit transmission of the pulse through the gain medium substantially independent of polarization.

12. The laser amplifier of claim 11, wherein the first and second faces of the gain medium have anti-reflective coatings.

13. The laser amplifier of claim 1, further comprising two telescopes mounted in the optical path, one for relaying an image adjacent the gain medium to a location adjacent the polarization rotator and the passive polarizer, and another for relaying the image back.

14. The laser amplifier of claim 11, wherein the telescope comprises a vacuum chamber, a first lense mounted with a vacuum tight seal at a first end of the vacuum chamber, and a second lense mounted with a vacuum tight seal at a second end of the vacuum chamber, and wherein the first and second lenses are mounted so that the optical path proceeds slightly off axis through the lenses so that the first and second lenses form the two telescopes.

15. The laser amplifier of claim 1, wherein the passive polarizer comprises an optical element mounted transverse to the optical path, and having first and second faces at near Brewster's angle reflecting a beam with a first polarization and transmitting a beam having a second polarization orthogonal to the first polarization.

16. The laser amplifier of claim 5 wherein the amplified output beam includes pulses with energy greater than 20 joules per pulse and peak power greater than a gigawatt.

17. The laser amplifier of claim 5 wherein when a beam from the generating means has a diffraction limited quality, and the amplified output pulse has substantially the same diffraction limited quality.

18. The laser amplifier of claim 1 wherein the beam includes pulses having a length more than one times a length of the optical path.

19. A laser amplifier capable of amplifying a laser pulse to a magnitude capable of generating X-rays used in the process of X-ray lithography for manufacturing integrated circuits, the amplifier comprising:

means for generating an input beam;

a gain medium;

a first polarization rotator;

a passive polarizer;

a plurality of reflectors configured to define an optical path through the gain medium, the passive polarizer, and the first polarization rotator;

a phase conjugator configured to receive a beam from the optical path after the beam has proceeded one or more transits through the optical path, the phase conjugator further configured to return the beam with reversed phase to the optical path to proceed an equal number of transits of the optical path in an opposite direction before exiting the optical path;

an external polarizer reflecting the beam from the generating means, the beam having a first polarization, but transmitting a beam with a second polarization; and

a second polarization rotator which receives the beam reflected from the external polarizer and transmits the beam with no polarization change into the optical path, and which receives the beam exiting the optical path and rotates the beam to the second polarization so that the beam will proceed through the external polarizer as an amplified output beam;

wherein a transit of the beam through the optical path includes a plurality of passes through the gain medium and only one pass through the polarization rotator and the passive polarizer.

20. A method of amplifying a laser beam comprising the steps of:

coupling a beam into a ring shaped optical path;

phase reversing the beam after one or more transits through the ring;

coupling passively the beam out of the ring after an equal number of transits through the ring in an opposite direction; and

increasing gain twice for each transit of the beam through the ring.

21. A laser amplifier, comprising:

a gain medium, including a source of pump energy, having an effective gain lifetime;

means, mounted with the gain medium, for establishing an optical path having path length including more than two passes through the gain medium within the effective gain lifetime of the gain medium; and

means, mounted with the gain medium, for coupling a beam into the optical path and out of the optical path, wherein the beam has a pulse length greater than the path length of the optical path;

wherein the means for establishing an optical path includes:

a plurality of reflectors configured to establish a ring in which each transit of the ring includes more than one pass through the gain medium, and

a phase conjugator configured to receive a pulse from the optical path after the pulse has proceeded one or more transits through the ring, the phase conjugator further configured to return the pulse to the ring to proceed an equal number of transits in an opposite direction before completing the optical path.

22. The laser amplifier of claim 21, wherein the means for coupling the beam into and out of the optical path includes:

an external polarizer reflecting a beam from a beam source with a first polarization, but transmitting a beam with a second polarization; and

an external polarization rotator which receives the beam reflected from the external polarizer and transmits the beam with no polarization change into the optical path, and which receives the beam from the optical path and rotates the beam to the second polarization so that the beam will proceed through the external polarizer as an amplified output beam.

23. A laser amplifier, comprising:

a gain medium, including a source of pump energy, having an effective gain lifetime;

means, mounted with the gain medium, for establishing an optical path having path length including more than two passes through the gain medium within the effective gain lifetime of the gain medium; and

means, mounted with the gain medium, for coupling a beam into the optical path and out of the optical path, wherein the beam has a pulse length greater than the path length of the optical path;

wherein the means for coupling the beam into and out of the optical path includes:

an external polarizer reflecting a beam from a beam source with a first polarization, but transmitting a beam with a second polarization; and

an external polarization rotator which receives the beam reflected from the external polarizer and transmits the beam with no polarization change into the optical path, and which receives the beam from the optical path and rotates the beam to the second polarization so that the beam will proceed through the external polarizer as an amplified output beam.

24. A laser amplifier, comprising:

a gain medium;

a polarization rotator;

a passive polarizer;

a plurality of reflectors configured to define an optical path through the gain medium, the passive polarizer, and the polarization rotator; and

a phase conjugator configured to receive a beam from the optical path after the pulse has proceeded one or more transits through the optical path, the phase conjugator further configured to return the beam with reversed phase to the optical path to proceed an equal number of transits of the optical path in an opposite direction before exiting the optical path;

wherein the gain medium includes first and second faces transverse to the optical path, and wherein the first and the second faces permit transmission of the pulse through the gain medium substantially independent of polarization;

wherein the first and second faces of the gain medium have anti-reflective coatings.

25. A laser amplifier, comprising:

a gain medium;

a polarization rotator;

a passive polarizer;

a plurality of reflectors configured to define an optical path through the gain medium, the passive polarizer, and the polarization rotator; and

a phase conjugator configured to receive a beam from the optical path after the pulse has proceeded one or more transits through the optical path, the phase conjugator further configured to return the beam with reversed phase to the optical path to proceed an equal number of transits of the optical path in an opposite direction before exiting the optical path;

a means for generating the beam with a first polarization;

an external polarizer reflecting the beam from the generating means with the first polarization, but transmitting a beam with a second polarization; and

an external polarization rotator which receives the beam reflected from the external polarizer and transmits the pulse with no polarization change into the optical path, and which receives the beam exiting the optical path and rotates the beam to the second polarization so that the beam will proceed through the external polarizer as an amplified output pulse;

wherein the amplified output pulses have energy greater than 20 joules per pulse and peak power greater than a gigawatt.

26. The laser amplifier of claim 23, wherein the external polarization rotator comprises a Faraday rotator.

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Appendix G

Video showing the marking of a gear with the Data Matrix symbol using Lasershot[sm] Marking System. The multiple-shot matrix marking technique is used to inscribe the 18x18 identification symbol on the helicopter gear shown in the photographs of Appendix B. The 3-minute presentation on the CD-ROM is in Quicktime format. A VHS tape copy is also provided.

SEE UCRL-MI-142507